Last lecture (2)

- Plasma physics 2
- Solar activity

Today's lecture (3)

- Magnetic reconnection ↔ solar flares
- Solar wind - basic facts
- Solar wind - magnetic structure

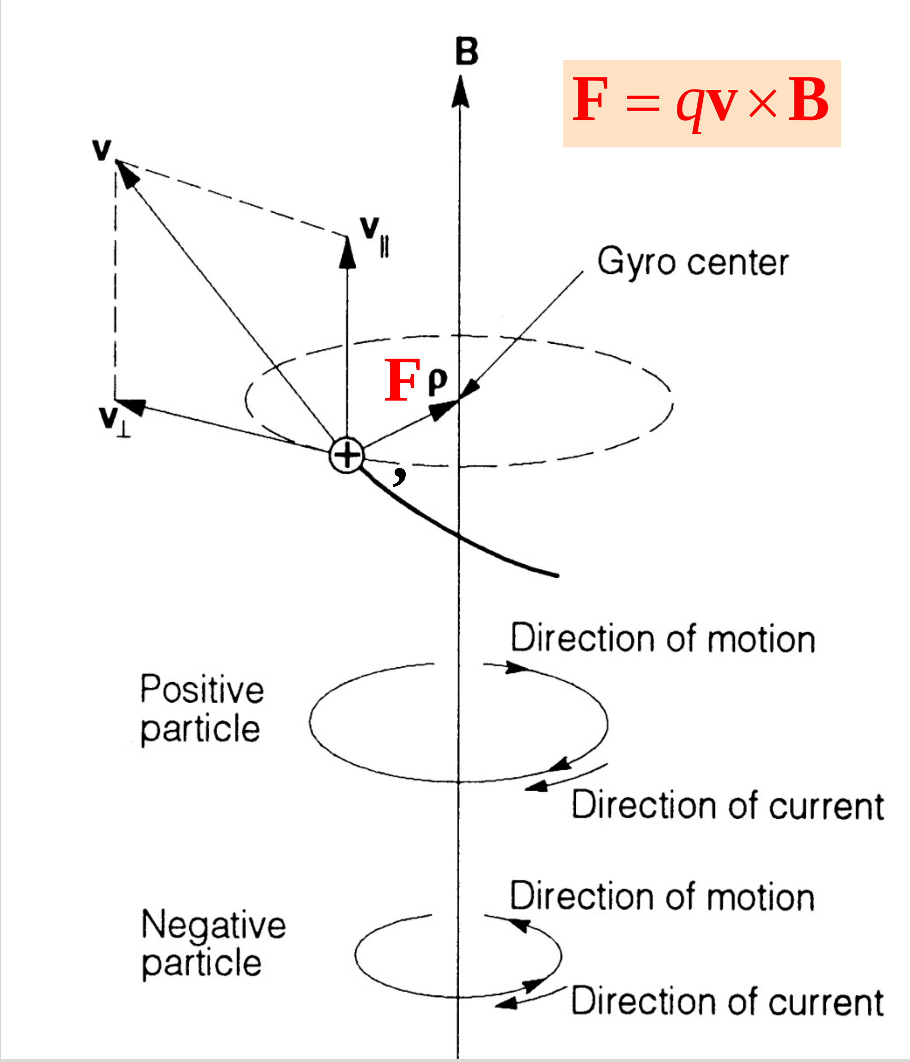
Today

Activity	Date	Time	Room	Subject	Litterature
L1	28/8	15-17	Q21	Course description, Introduction, The Sun 1	**CGF** Ch 1.1,1.2, 1.4, 5, (p 110-113), 6.3
L2	29/8	13-15	Q2	The Sun 2, Plasma physics 1	**CGF** Ch 1.3, 5 (p 114-121)
L3	4/9	10-12	E2	Solar wind, The ionosphere and atmosphere 1, Plasma physics 2	**CGF** Ch 6.1, 2, 3.1-3.2, 3.5, **LL** Ch III, Extra material
T1	6/9	8-10	Q21	Mini-group work 1	
L4	6/9	15-17	Q2	The ionosphere 2, Plasma physics 3	**CGF** Ch 3.4, 3.7, 3.8
T2	10/9	15-17	Q21	Mini-group work 2	
L5	11/9	10-12	E3	The Earth's magnetosphere 1, Plasma physics 4	**CGF** 4-1-4.3, **LL** Ch I, II, IV.A
T3	17/9	8-10	Q21	Mini-group work 3	
L6	18/9	13-15	Q33	The Earth's magnetosphere 2, Other magnetospheres	**CGF** Ch 4.6-4.9, **LL** Ch V.
L7	19/9	13-15	Q2	Aurora, Measurement methods in space plasmas and data analysis 1	**CGF** Ch 4.5, 10**, LL** Ch VI, Extra material
T4	24/9	8-10	Q2	Mini-group work 4	
L8	24/9	15-17	V3	Space weather and geomagnetic storms	**CGF** Ch 4.4, **LL** Ch IV.B-C, VII.A-C
T5	2/10	8-10	Q31	Mini-group work 5	
L9	2/10	13-15	Q2	Alfvén waves, Interstellar and intergalactic plasma, Cosmic radiation	**CGF** Ch 7-9, Extra material
T6	8/10	15-17	Q21		
L10	9/10	10-12	Q2	Guest Lecture by Swedish astronaut Christer Fuglesang	
Written examination	16/10	14-19	L21, L22, L31		

Magnetized plasma

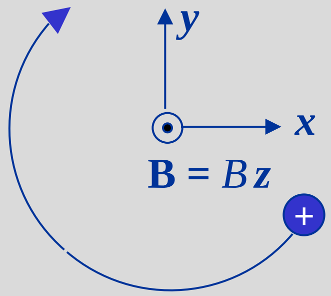
Extremely common in space.

In single particle description of plasma, the particles gyrate in the plane perpendicular to **B**.



Gyro motion

Consider a positively charged particle in a magnetic field.



Assume that the magnetic field is in the z-direction.

$$m\frac{d\mathbf{v}}{dt} = q\mathbf{v} \times \mathbf{B} \Rightarrow$$

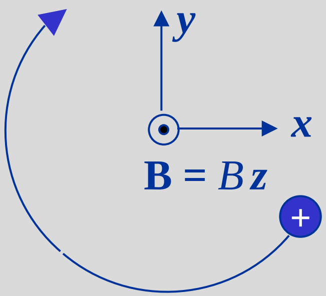
$$\begin{cases} m\dfrac{dv_x}{dt} = qv_yB \\ m\dfrac{dv_y}{dt} = -qv_xB \\ m\dfrac{dv_z}{dt} = 0 \end{cases} \Rightarrow$$

Constant velocity along $\mathbf{z}$

$$\begin{cases} \dfrac{d^2v_x}{dt^2} = \dfrac{qB}{m}\dfrac{dv_y}{dt} = \omega_g\dfrac{dv_y}{dt} = -\omega_g^2 v_x \\ \dfrac{d^2v_y}{dt^2} = -\dfrac{qB}{m}\dfrac{dv_x}{dt} = -\omega_g\dfrac{dv_x}{dt} = -\omega_g^2 v_y \end{cases}$$

$\Rightarrow$

Gyro motion



$$\begin{cases} \dfrac{d^2 v_x}{dt^2} = -\omega_g^2 v_x \\ \dfrac{d^2 v_y}{dt^2} = -\omega_g^2 v_y \end{cases}$$

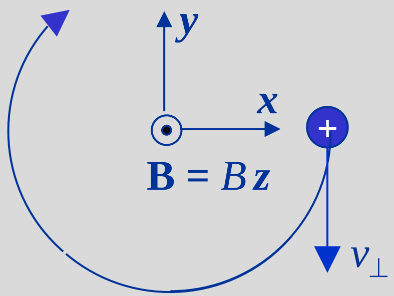
$\Rightarrow$

$$\begin{cases} v_x = Re\left(v_{0x} e^{i(\omega_g t + \delta_x)}\right) = v_{0x} cos(\omega_g t + \delta_x) \\ v_y = Re\left(v_{0y} e^{i(\omega_g t + \delta_y)}\right) = v_{0y} cos(\omega_g t + \delta_y) \end{cases}$$

and

$$\begin{cases} x = \dfrac{v_{0x}}{\omega_g} sin(\omega_g t + \delta_x) \\ y = \dfrac{v_{0y}}{\omega_g} sin(\omega_g t + \delta_y) \end{cases}$$

Gyro motion



$$\begin{cases} v_x = v_{0x}cos(\omega_g t + \delta_x) \\ v_y = v_{0y}cos(\omega_g t + \delta_y) \end{cases}$$

$$\begin{cases} x = \dfrac{v_{0x}}{\omega_g} sin(\omega_g t + \delta_x) \\ y = \dfrac{v_{0y}}{\omega_g} sin(\omega_g t + \delta_y) \end{cases}$$

For a particle starting at time t=0 at (x_0,0) with velocity (0,-$v_\perp$)
we get (by definition v_{0x}, v_{0x} > 0)

$$\begin{cases} v_y(0) = v_{0y}cos\delta_y = -v_\perp & \Rightarrow\ v_{0y} = v_\perp, \delta_y = \pi \\ v_x(0) = v_{0x}cos\delta_x = v_{0x}cos\delta_x = 0 & \Rightarrow\ \delta_x = \dfrac{\pi}{2}, \dfrac{3\pi}{2} \end{cases}$$

and

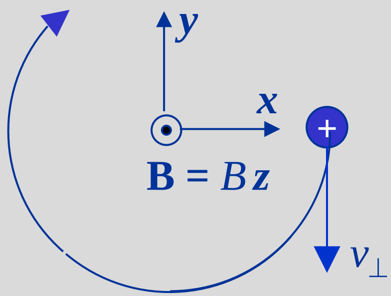
$$\begin{cases} x(0) = \dfrac{v_{0x}}{\omega_g}\sin\delta_x = x_0 & \Rightarrow\ \delta_x = \dfrac{\pi}{2},\ x_0 = \dfrac{v_{0x}}{\omega_g} \\ y(0) = \dfrac{v_\perp}{\omega_g}\sin\pi = 0 & \end{cases}$$

So

$$\begin{cases} v_x = v_{0x}cos\left(\omega_g t + \dfrac{\pi}{2}\right) = -v_{0x}sin(\omega_g t) \\ v_y = v_\perp cos(\omega_g t + \pi) = -v_\perp cos(\omega_g t) \end{cases}$$

$$\begin{cases} x = \dfrac{v_{0x}}{\omega_g} sin\left(\omega_g t + \dfrac{\pi}{2}\right) = \dfrac{v_{0x}}{\omega_g} cos(\omega_g t) = \dfrac{v_{0x}}{\omega_g} cos(-\omega_g t) \\ y = \dfrac{v_\perp}{\omega_g} sin(\omega_g t + \pi) = -\dfrac{v_\perp}{\omega_g} sin(\omega_g) = \dfrac{v_\perp}{\omega_g} sin(-\omega_g t) \end{cases}$$

Gyro motion



$$\begin{cases} v_x = -v_{0x}\sin(\omega_g t) \\ v_y = -v_\perp \cos(\omega_g t) \end{cases}$$

$$\begin{cases} x = \dfrac{v_{0x}}{\omega_g}\cos(-\omega_g t) \\ y = \dfrac{v_\perp}{\omega_g}\sin(-\omega_g t) \end{cases}$$

Then (because the force is all the time perpendicular to the velocity)

$$v_x{}^2 + v_y{}^2 = v_{0x}{}^2 sin^2(\omega_g t) + v_\perp{}^2 cos^2(\omega_g t) = v_\perp{}^2$$

so

$$v_{0x} = v_\perp$$

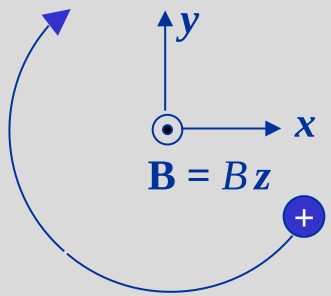
So

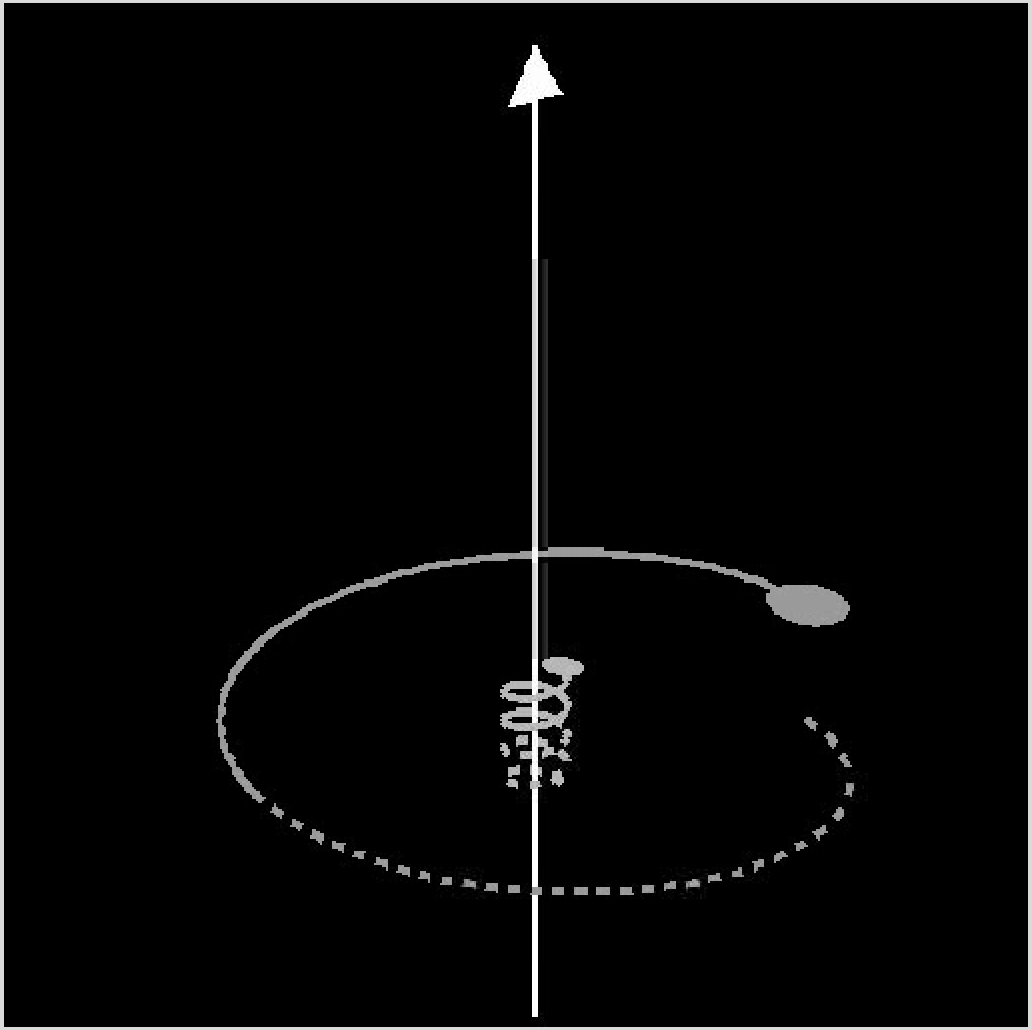
$$\begin{cases} x = \dfrac{v_\perp}{\omega_g}\cos(-\omega_g t) \\ y = \dfrac{v_\perp}{\omega_g}\sin(-\omega_g t) \end{cases}$$

and

$$x^2 + y^2 = \frac{v_\perp{}^2}{\omega_g{}^2} \equiv r_L{}^2 = \varrho^2$$

Gyro motion





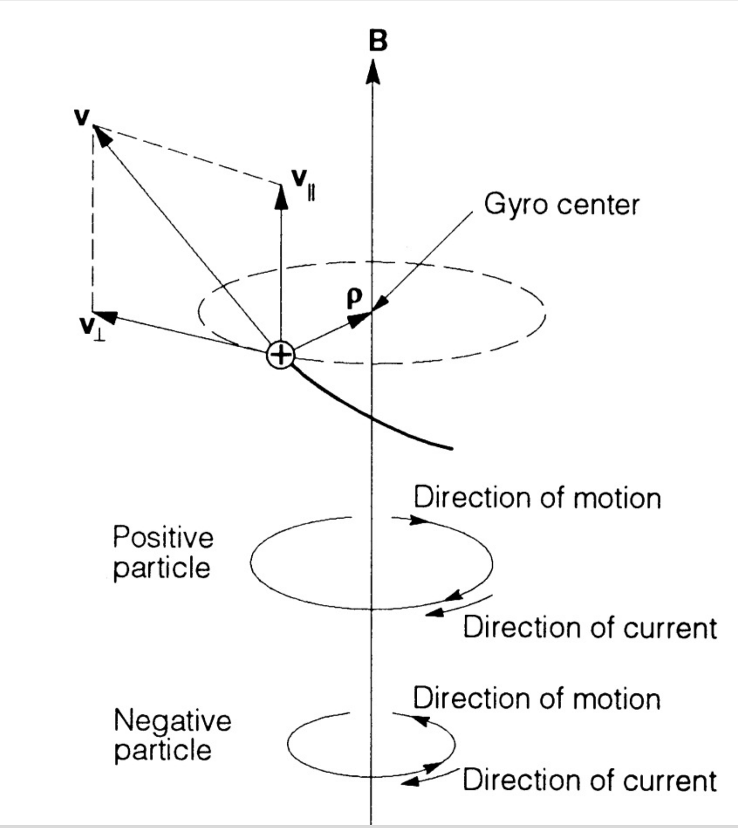
Then

$$x = r_L cos(-\omega_g t)$$
$$y = r_L sin(-\omega_g t)$$

$$\omega_g = \frac{qB}{m}$$

$$r_L = \frac{mv_\perp}{qB}$$

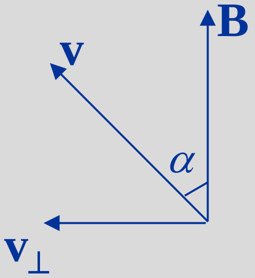
Gyro radius



Magnetic force: $\mathbf{F} = q\mathbf{v}_\perp \times \mathbf{B}$

Centripetal force: $\mathbf{F} = \dfrac{mv_\perp^2}{\rho}\hat{\boldsymbol{\rho}}$

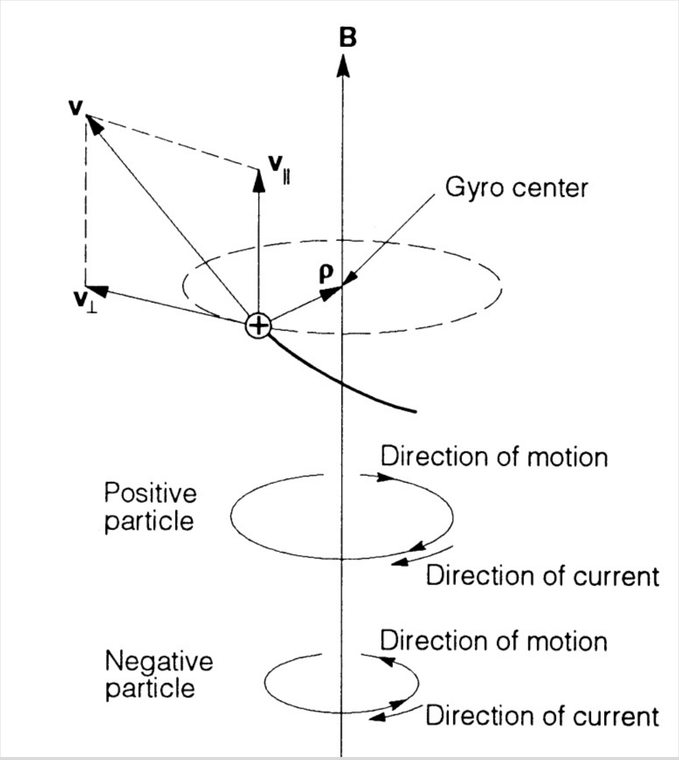
$\Leftrightarrow$



$v_\perp = v \cdot \sin\alpha$

$$\boxed{\rho = \frac{mv_\perp}{qB}}$$

Gyro frequency



$$\rho = \frac{mv_\perp}{qB}$$

$$\omega\rho = v_\perp$$

$$\Rightarrow$$

$$\boxed{\omega_g = \frac{qB}{m}}$$

$$\omega = 2\pi f$$

Maxwell's equations

Gauss' law

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

No magnetic monopoles

$$\nabla \cdot \mathbf{B} = 0$$

Faraday's law

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

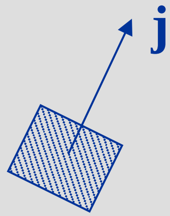
Ampére's law

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Lorentz' force equation

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Ohm's law



$$\mathbf{j} = \sigma \mathbf{E}$$

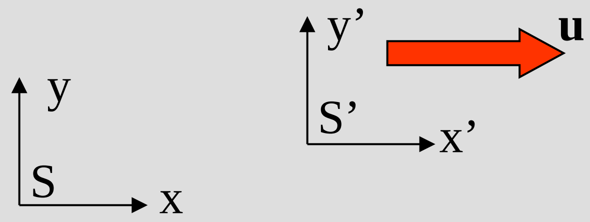
Energy density

$$W_B = \frac{B^2}{2\mu_0}, \quad W_E = \varepsilon_0 \frac{E^2}{2}$$

$$\nabla \cdot \mathbf{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$

$$\nabla \times \mathbf{A} = \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}, \frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}, \frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \right)$$

Field transformations (relativistic)



Relativistic transformations (perpendicular to the velocity $\mathbf{u}$*):*

$$\mathbf{E}' = \frac{\mathbf{E} + \mathbf{u} \times \mathbf{B}}{\sqrt{1 - u^2/c^2}}$$

$$\mathbf{B}' = \frac{\mathbf{B} - \left(\mathbf{u}/c^2\right) \times \mathbf{E}}{\sqrt{1 - u^2/c^2}}$$

For $u << c$*:*

$$\mathbf{E}' = \mathbf{E} + \mathbf{u} \times \mathbf{B}$$

induced electric field

$$\mathbf{E} = \mathbf{E}' - \mathbf{u} \times \mathbf{B}$$

$$\mathbf{B}' = \mathbf{B}$$

Frozen in magnetic flux *PROOF*

(1) $\mathbf{j} = \sigma \mathbf{E}' = \sigma\left(\mathbf{E} + \mathbf{v}\times\mathbf{B}\right)$ Ohm's law

(2) $\mu_0 \mathbf{j} = \nabla\times\mathbf{B} - \cancel{\frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}}$ Ampère's law

(3) $\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$ Faraday's law

$(1) \Rightarrow \quad \mathbf{E} = \frac{\mathbf{j}}{\sigma} - \mathbf{v}\times\mathbf{B}$

$(3{+}1) \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\left(\frac{\mathbf{j}}{\sigma} - \mathbf{v}\times\mathbf{B}\right)$

$(2) \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\left(\frac{\nabla\times\mathbf{B}}{\mu_0\sigma} - \mathbf{v}\times\mathbf{B}\right)$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times\left(\mathbf{v}\times\mathbf{B}\right) - \frac{1}{\mu_0\sigma}\nabla\times\left(\nabla\times\mathbf{B}\right) =$$

$$\nabla\times\left(\mathbf{v}\times\mathbf{B}\right) - \frac{1}{\mu_0\sigma}\left(\cancel{\nabla\left(\nabla\cdot\mathbf{B}\right)} - \nabla^2\mathbf{B}\right)$$

$$\therefore \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla\times\left(\mathbf{v}\times\mathbf{B}\right) + \frac{1}{\mu_0\sigma}\nabla^2\mathbf{B}$$

Frozen in magnetic flux *PROOF II*

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{v} \times \mathbf{B})}_{A} + \underbrace{\frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}}_{B}$$

Order of magnitude estimate:

$$\frac{A}{B} = \frac{\nabla \times (\mathbf{v} \times \mathbf{B})}{\frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}} \approx \frac{\frac{v \Delta B}{L}}{\frac{\Delta B}{\mu_0 \sigma L^2}} = v L \mu_0 \sigma \equiv R_m$$

Magnetic Reynolds number R_m:

$$\mathrm{R_m} >> 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Frozen-in fields!

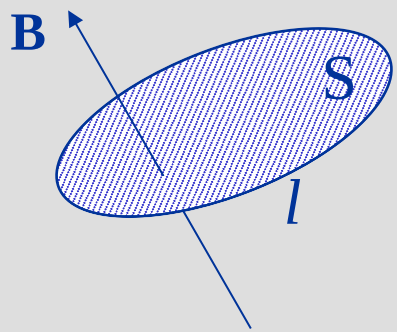
$$\mathrm{R_m} << 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

Diffusion equation!

Frozen in magnetic flux *PROOF III*

$$R_m >> 1 \Rightarrow \boxed{\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})}$$

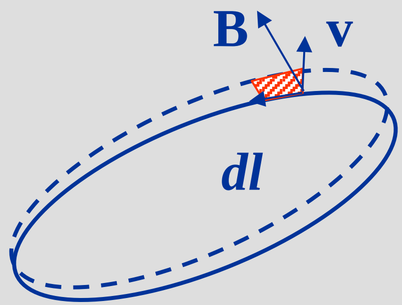
Consider the change of magnetic flux Φ through a surface S with contour l which follows plasma motion



$$\Phi = \int_S \mathbf{B} \cdot d\mathbf{S}$$

$$\frac{d\Phi}{dt} = \int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} + \frac{d\Phi_c}{dt}$$

$\frac{d\Phi_c}{dt}$ This term is due to change in the surface S due to plasma motion

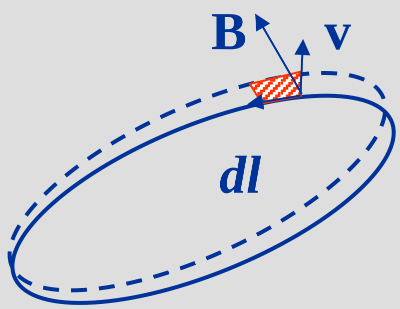


has an area of $(\mathbf{v} \cdot dt) \times d\mathbf{l}$

The flux through is $(\mathbf{v} \cdot dt) \times d\mathbf{l} \cdot \mathbf{B}$

$$\because \frac{d\Phi_c}{dt} = \int_l \mathbf{v} \times d\mathbf{l} \cdot \mathbf{B} =$$

Frozen in magnetic flux *PROOF IV*



$$\frac{d\Phi_c}{dt} = \int_l \mathbf{v} \times d\mathbf{l} \cdot \mathbf{B} =$$

$$-\int_l \mathbf{v} \times \mathbf{B} \cdot d\mathbf{l} = -\int_S \nabla \times (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{S}$$

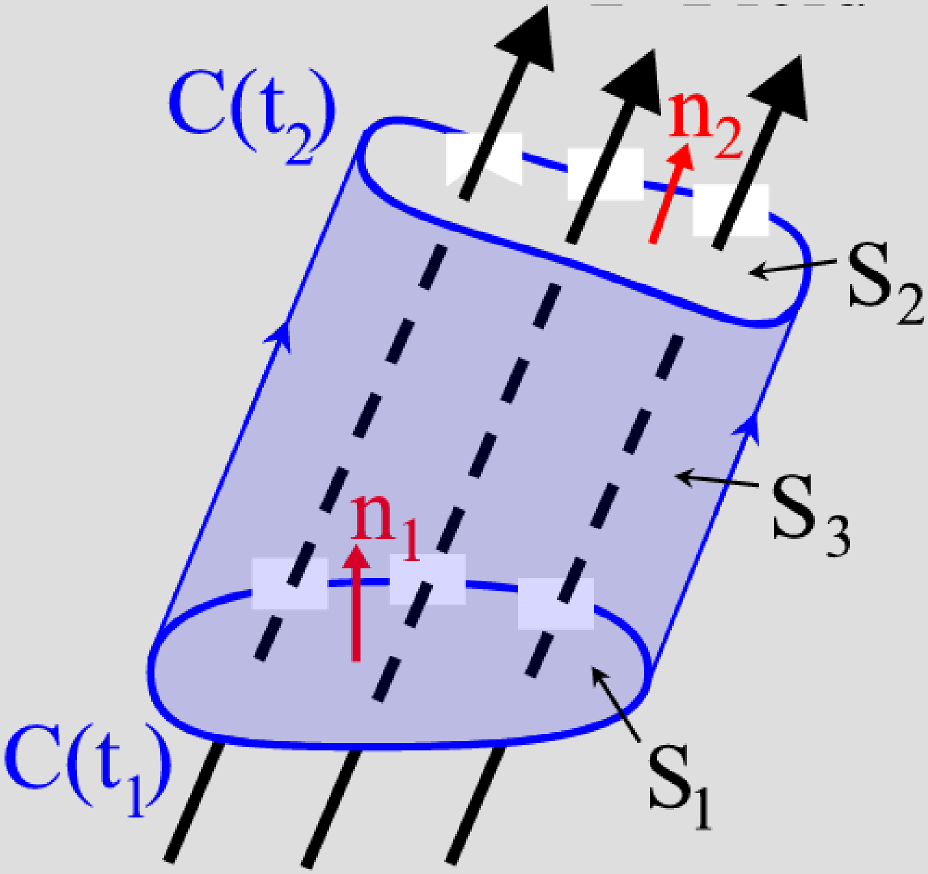
$$\because \frac{d\Phi}{dt} = \int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} - \int_S \nabla \times (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{S} =$$

$$\int_S \left[\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) \right] \cdot d\mathbf{S} = 0$$

★

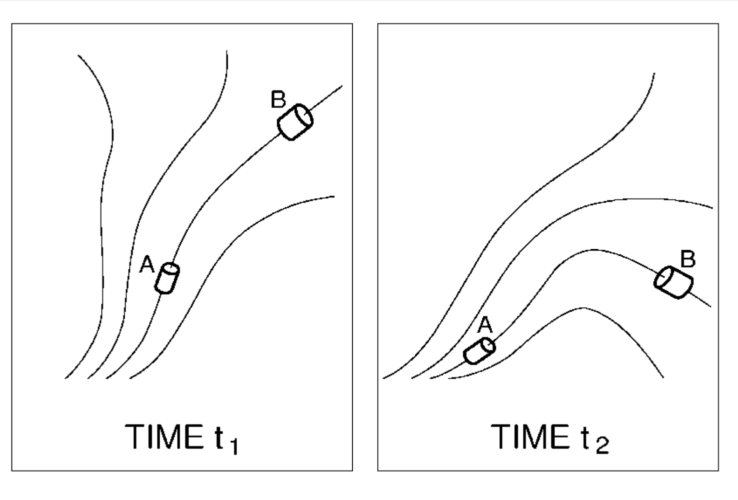
$$\because \frac{d\Phi}{dt} = 0$$

Frozen in magnetic field lines

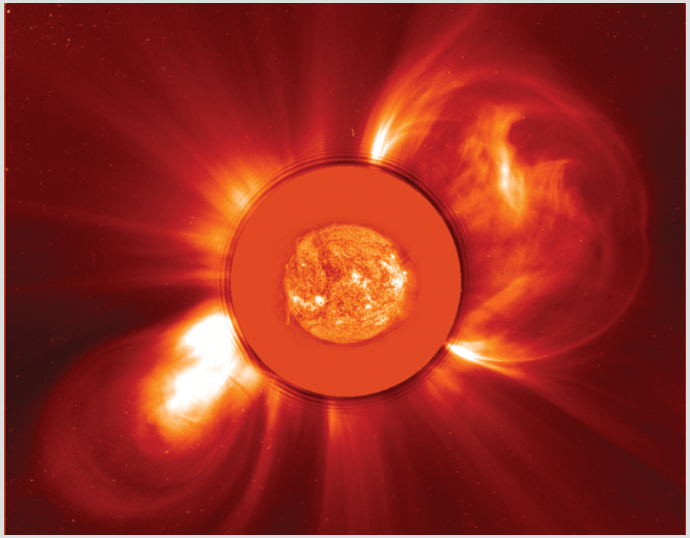


A *flux tube* is defined by following **B** from the surface S. Due to the frozen-in theorem the flux tube keeps its identity and the plasma in a flux tube stays in it for ever.

In particular if we let the tube become infinitely thin we have the theorem of frozen-in field lines.



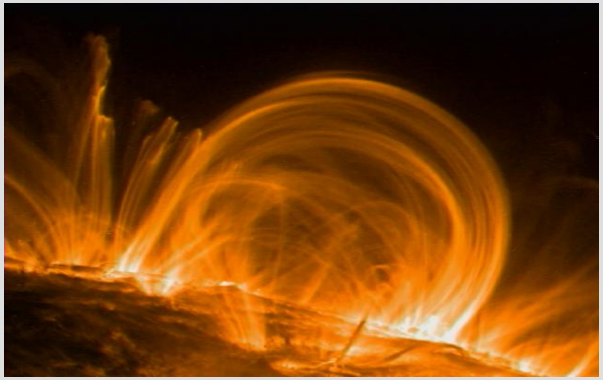
Magnetized plasma



Solar magnetic field

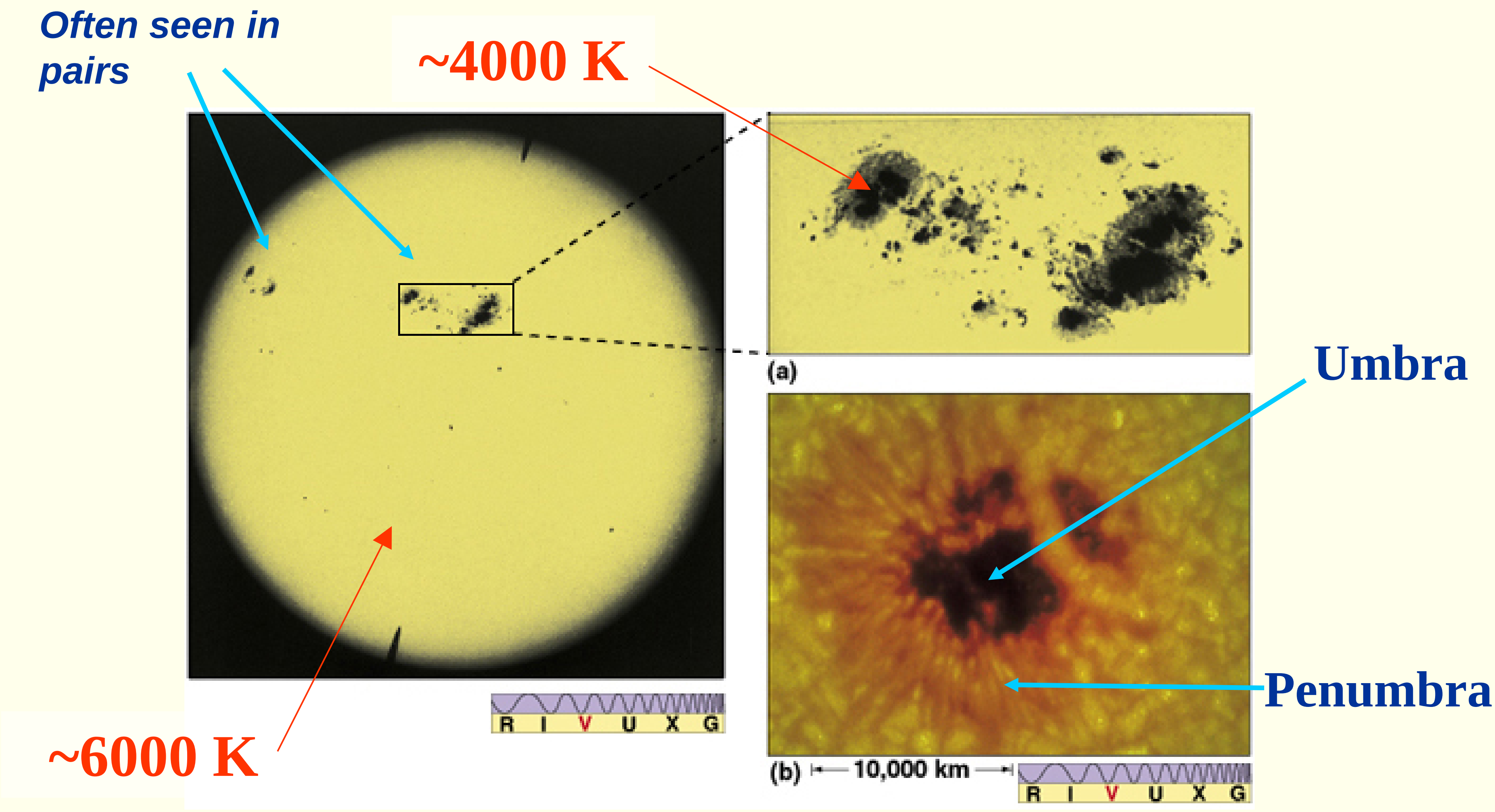
Northern lights (aurora)

Different *plasma populations* (plasmas with different temperature and density) keep to their own field line, and thus “paint out” the magnetic field lines.



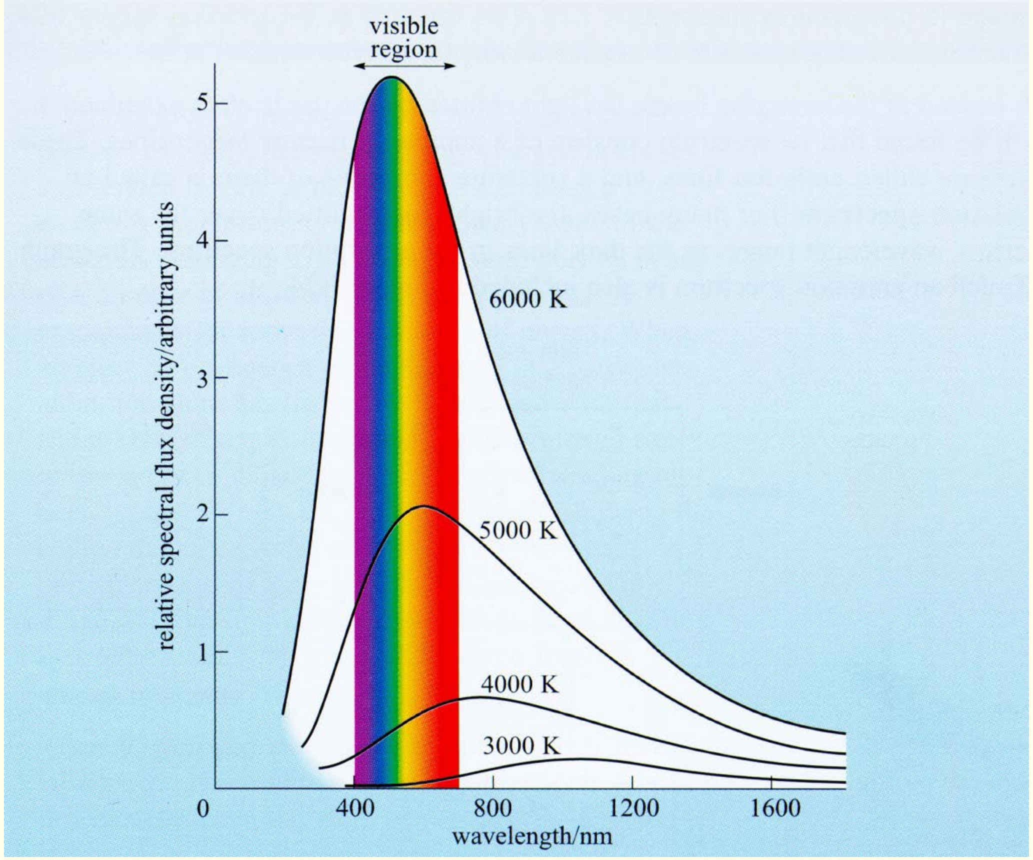
Coronal loop

Sunspots



Often seen in pairs
~4000 K
~6000 K
Umbra
Penumbra
(a)
(b)
10,000 km
R I V U X G
R I V U X G

Black-body radiation



Black-body good approximation for opaque bodies where emitted light is much more likely to interact with the material of the source than to escape.

Wien's displacement law

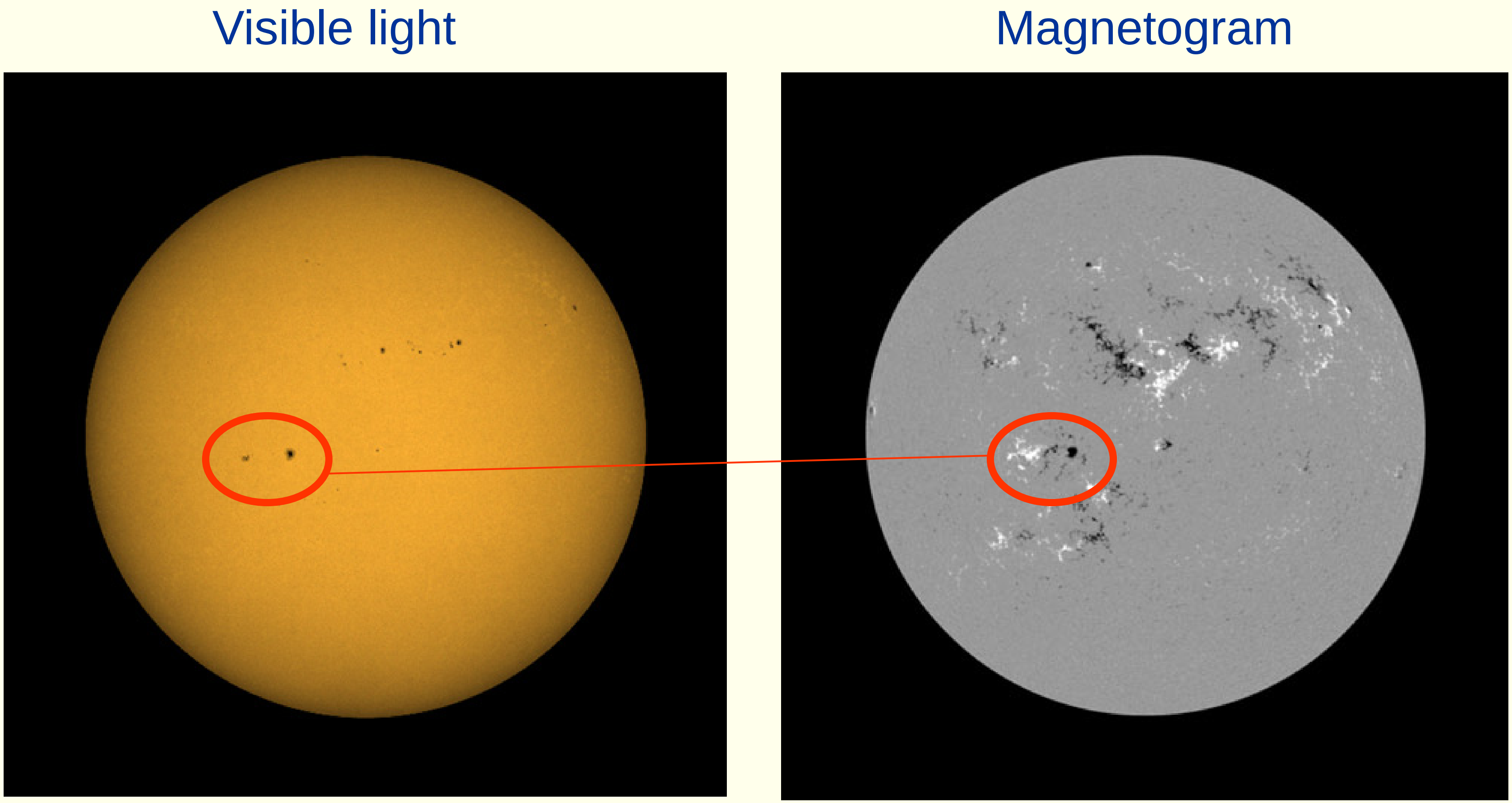
$$\lambda_{peak} = \frac{2.90 \times 10^{-3}}{T}$$

Stefan-Bolzmanns law

$$J = \sigma_{SB} T^4$$

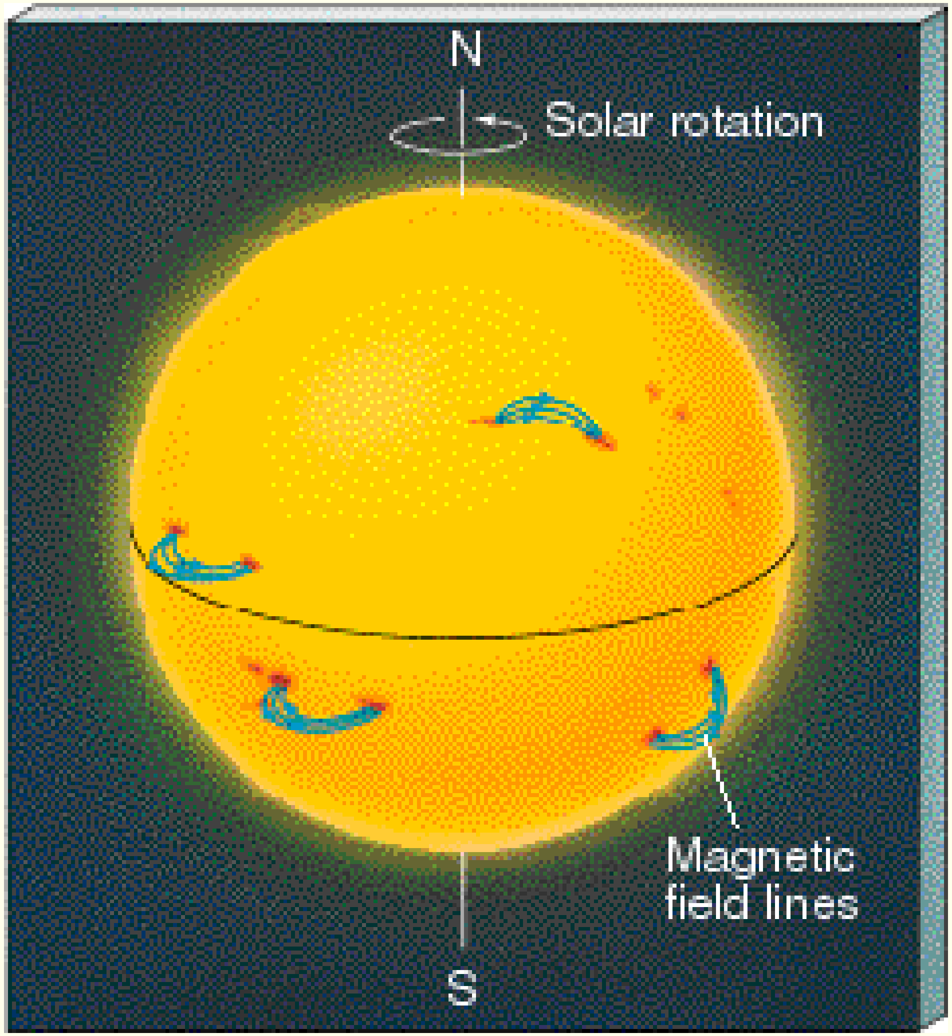
(J = total energy radiated per unit area per unit time)

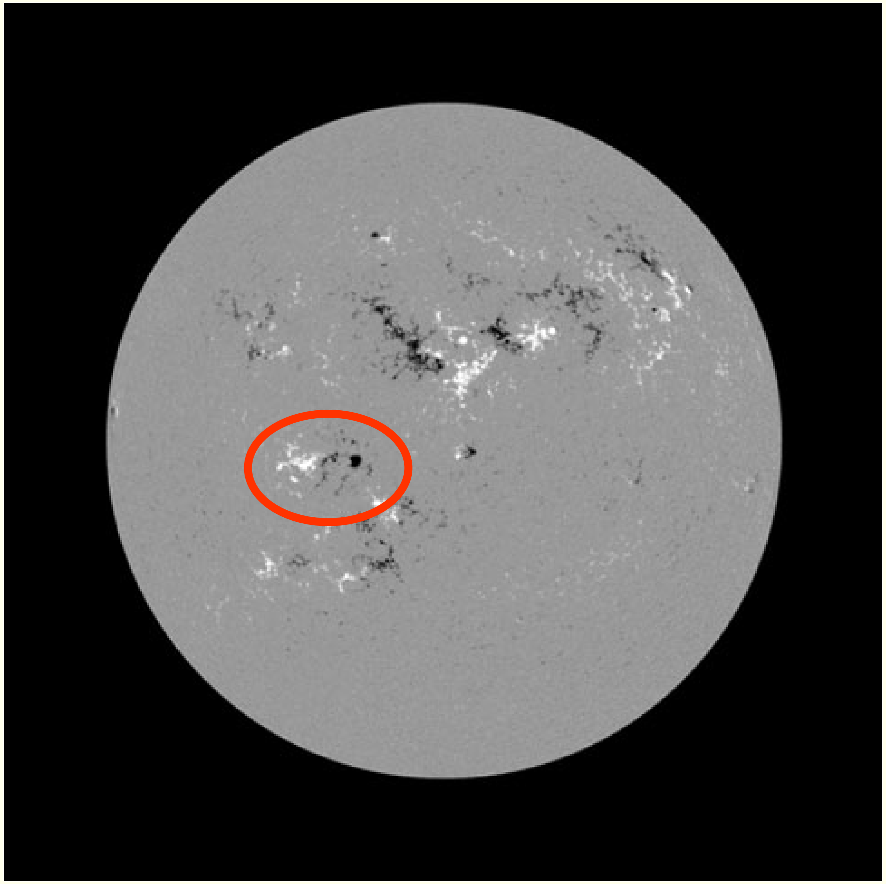
Sunspots and magnetic fields



Sunspots are associated with large magnetic fields

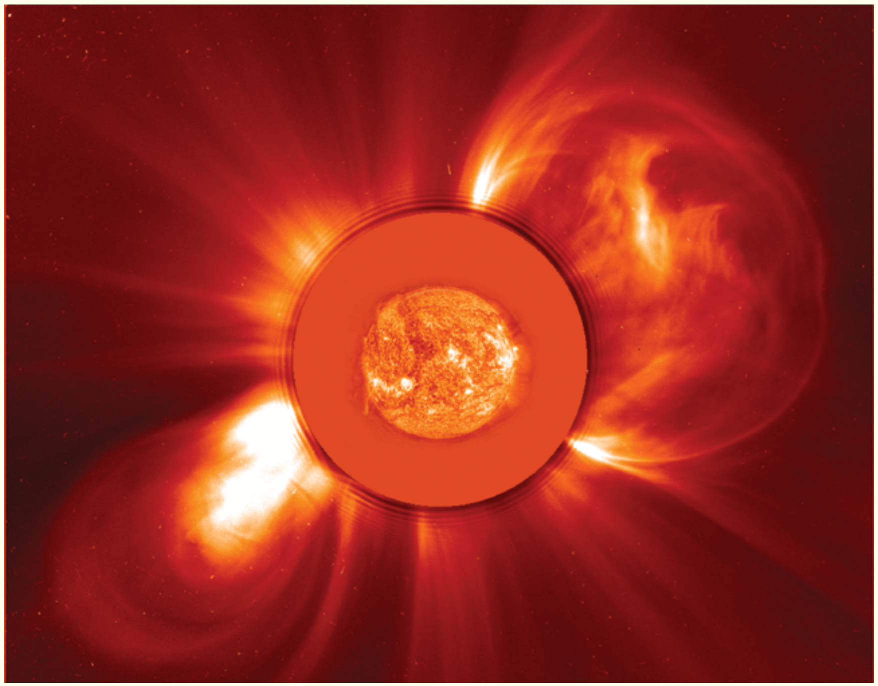
Sunspots and magnetic fields

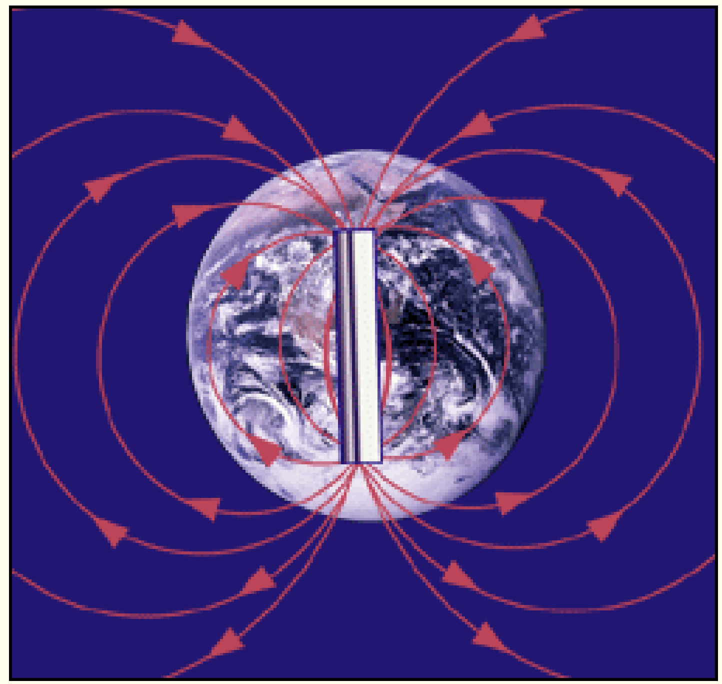




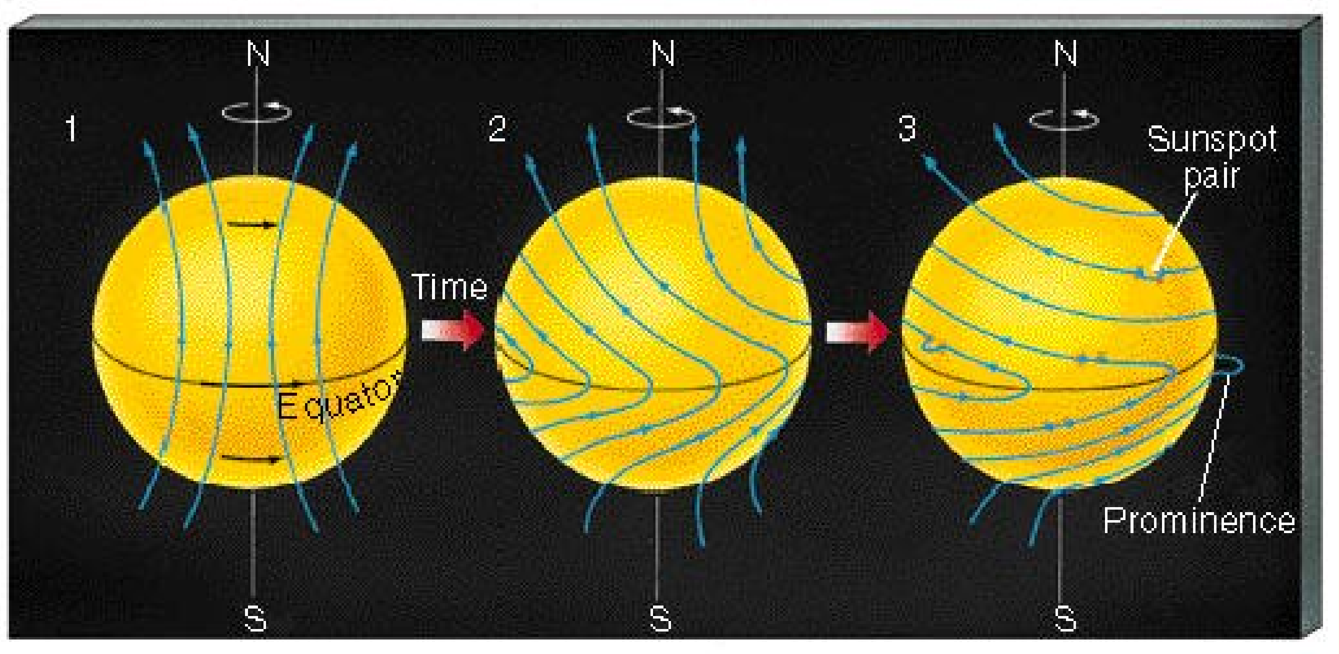
Sun's magnetic field

First guess/approximation:
a dipole field, just as Earth





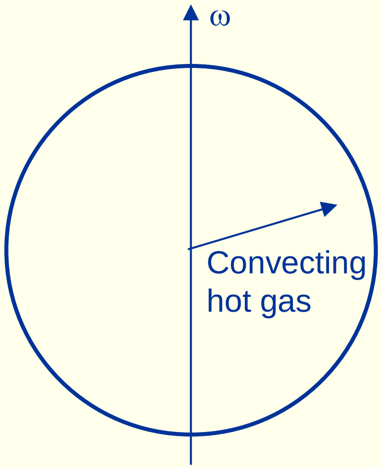
Sunspots and magnetic fields



Sun's rotational period as function of latitude λ

$$T_{rot} = \frac{25}{\left(1 - 0.19 sin^2 \lambda\right)}$$

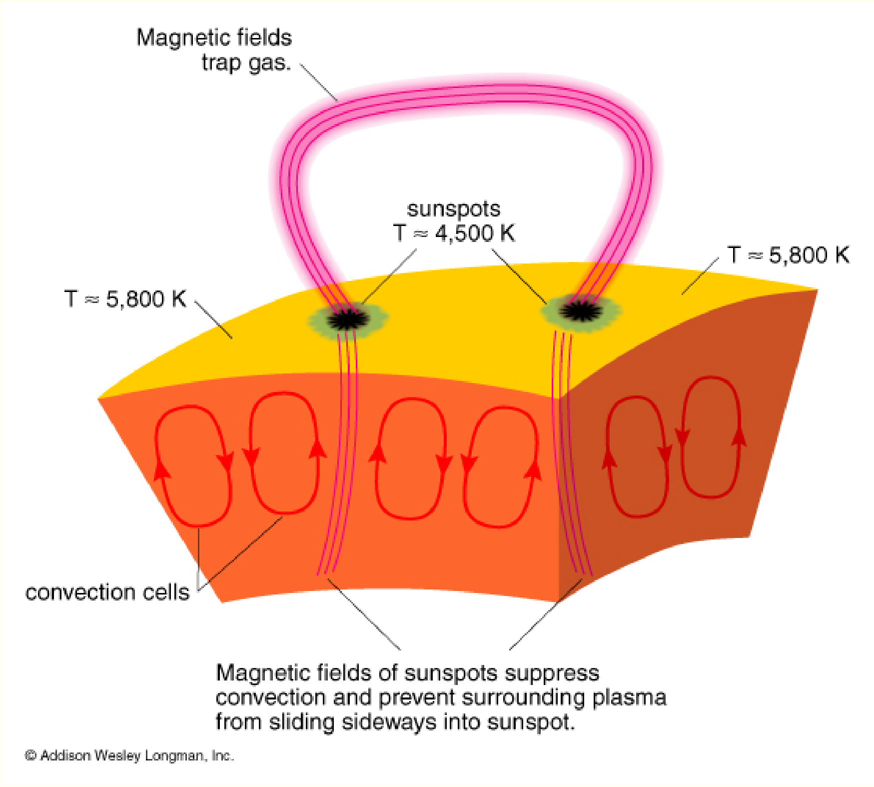
Differential rotation

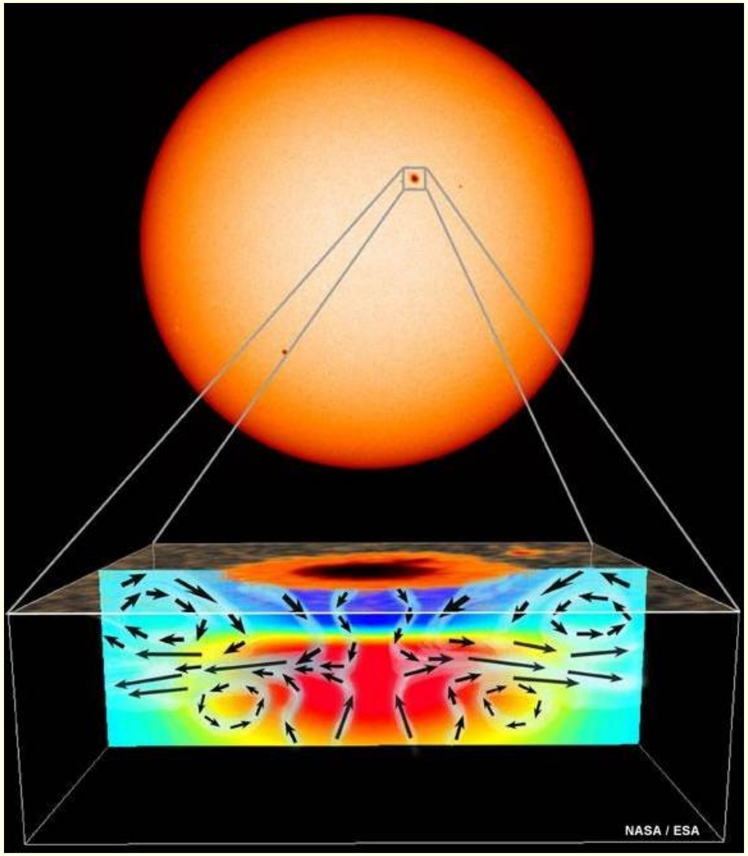


Differential rotation deforms the magnetic field lines. Sometimes a part of the field line may protrude ionto the solar atmosphere and cause loop, which may be associated with a pair of sunspots. (More complicated behaviour may of course also occur.)

Sunspots and magnetic fields

Sunspots

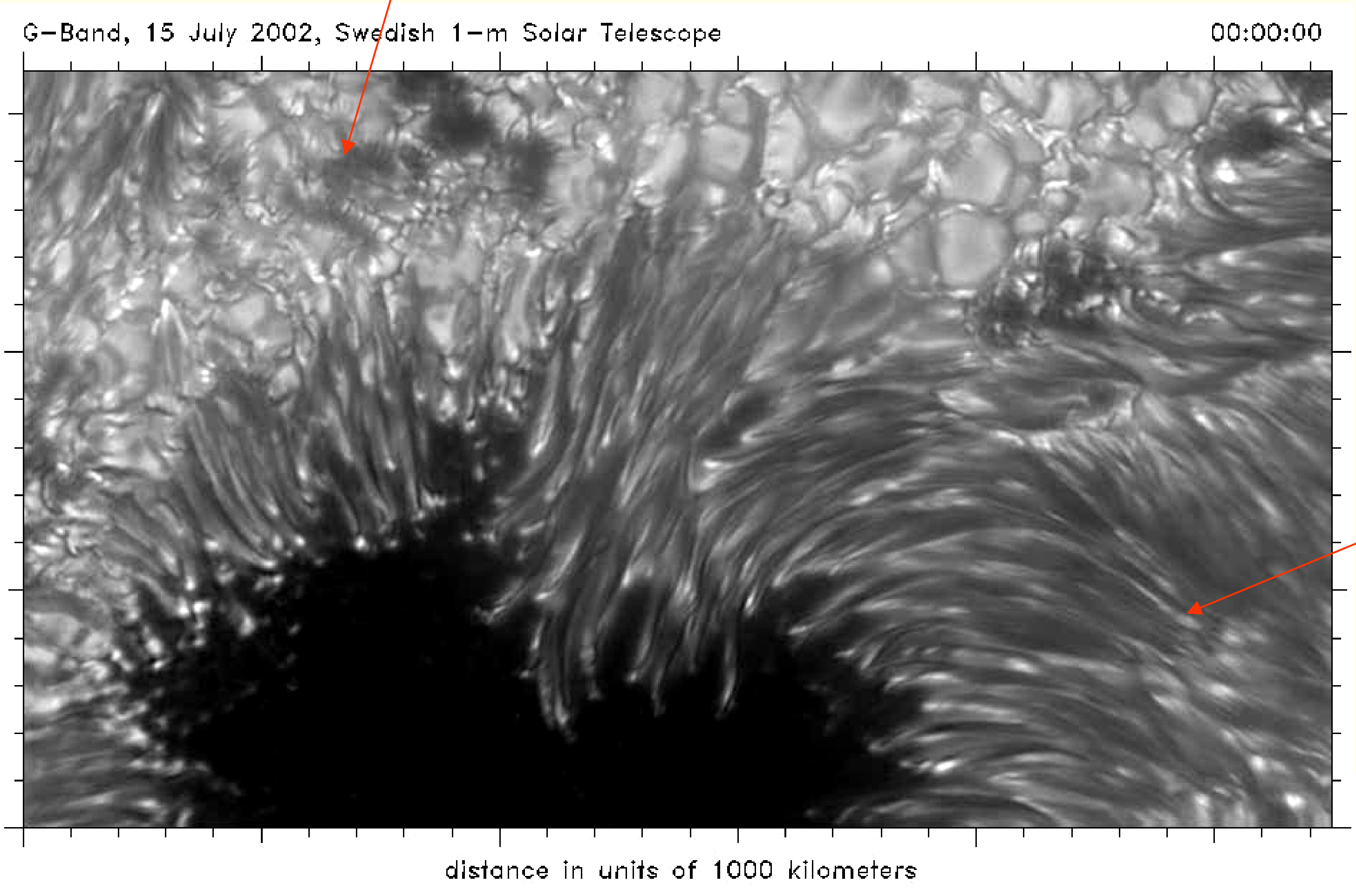




One theory is that the large magnetic field in the sunpots affects the convection of hot matter from the solar interior, so that it will not reach the surface.

Sunpots, convection

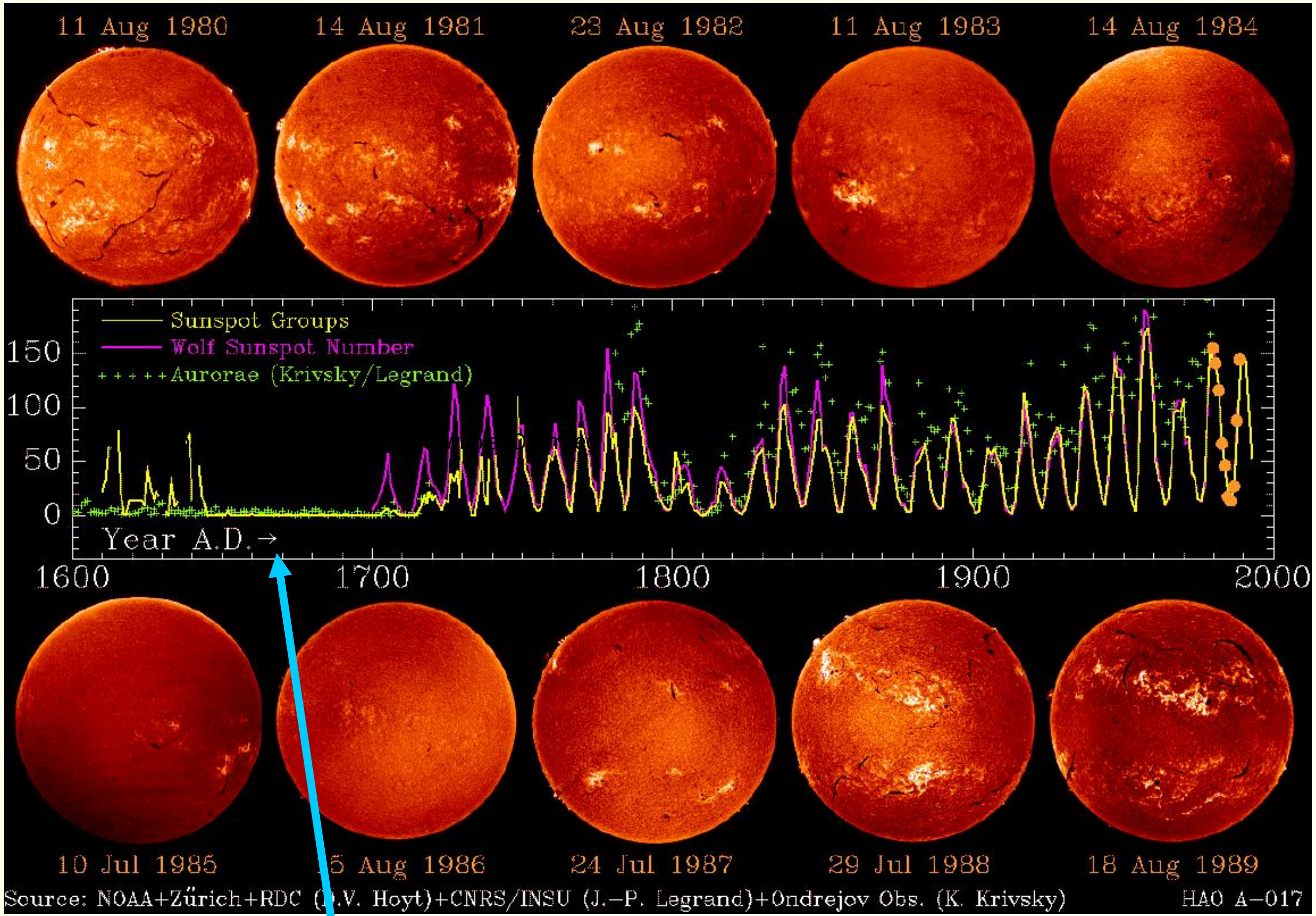
Convection cells (granulation)



Convection cell patter perturbed by magnetic field

Sunspot cycle (solar cycle)

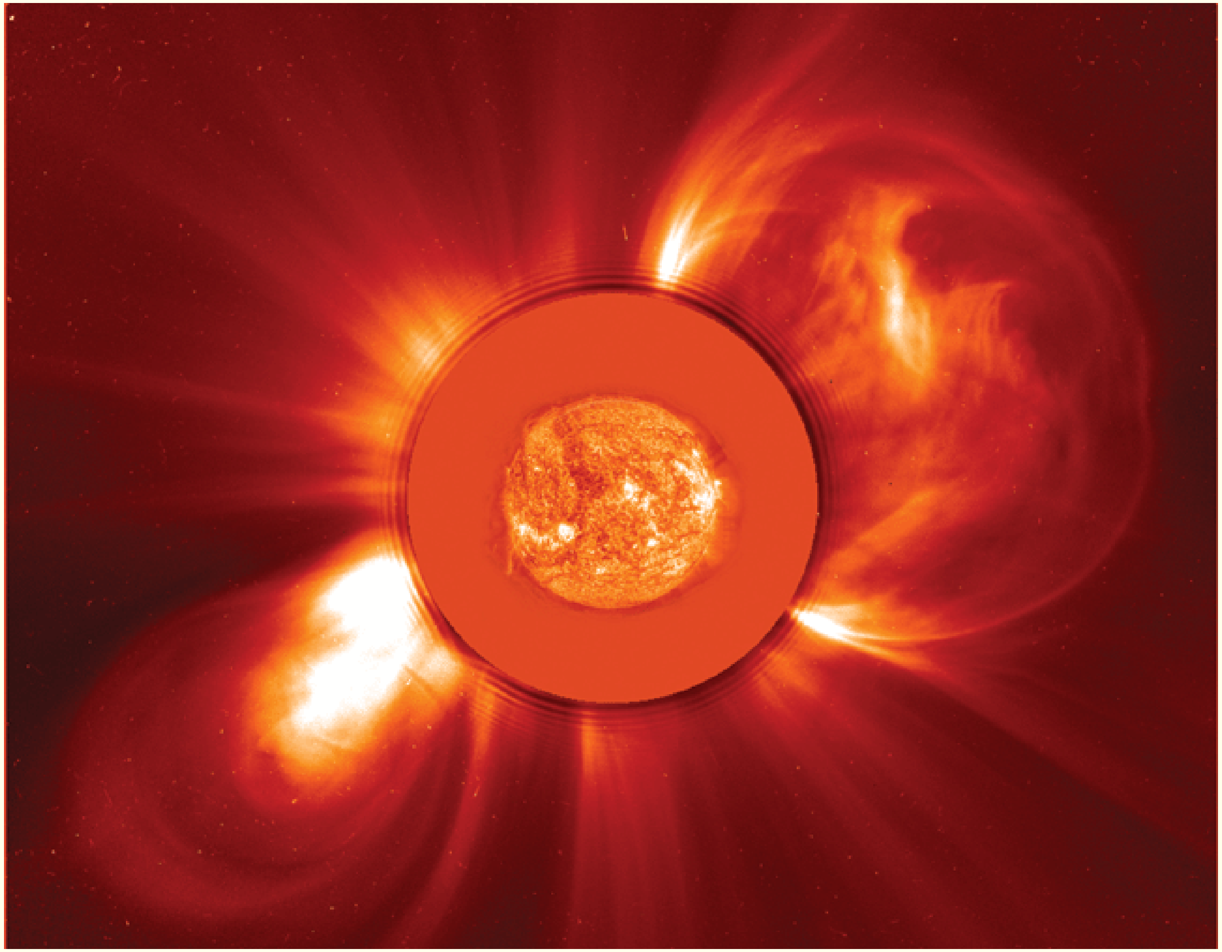
- T ≈ 11 ± 1 years
- The solar cycle is a manifestation of the changing solar magnetic field
- The Maunder minimum was associated with cold climate and no aurora.



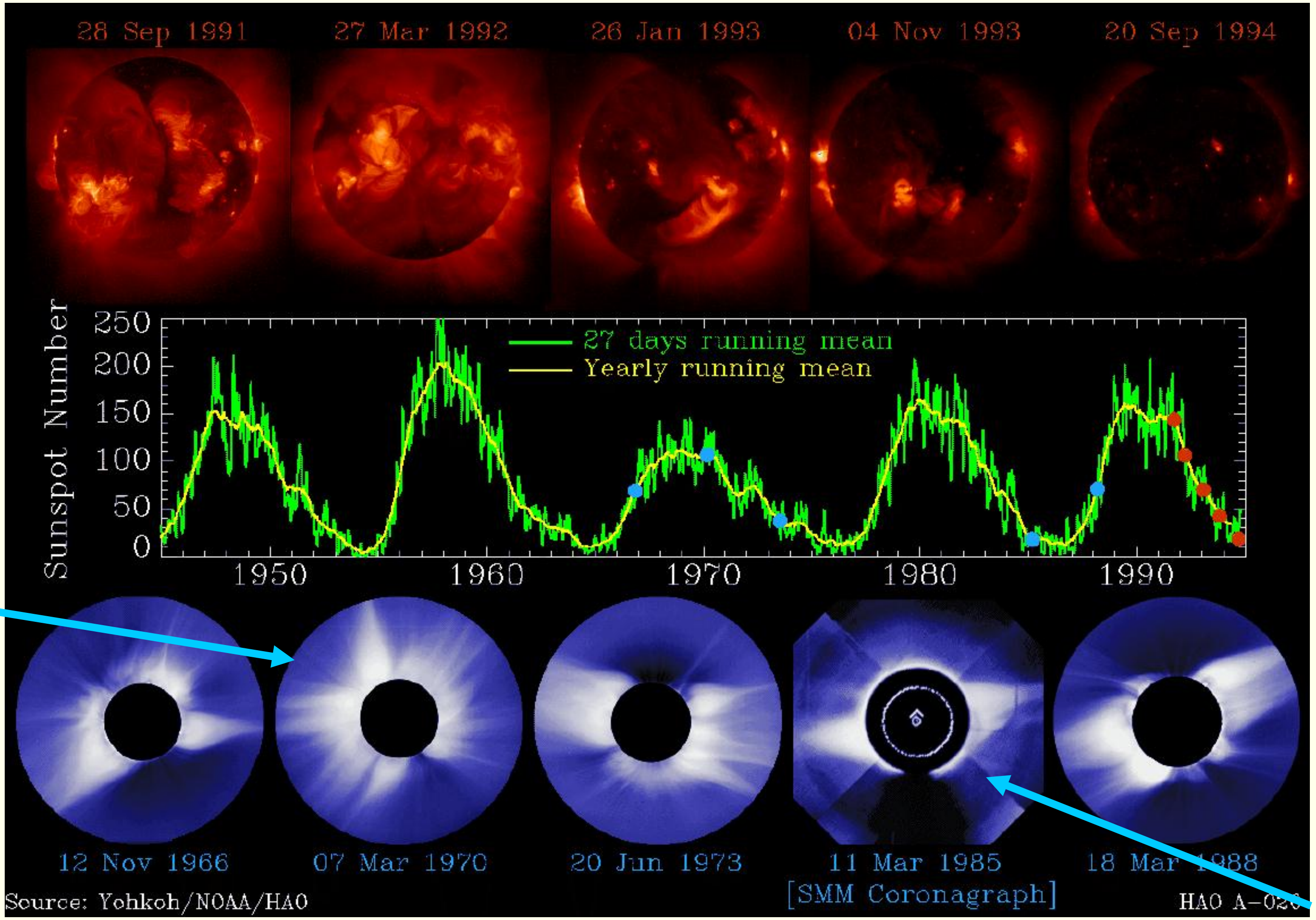
Maunder minimum

Solar magnetic field as organizing factor

Sun's dipole magnetic field



Solar magnetic field as organizing factor

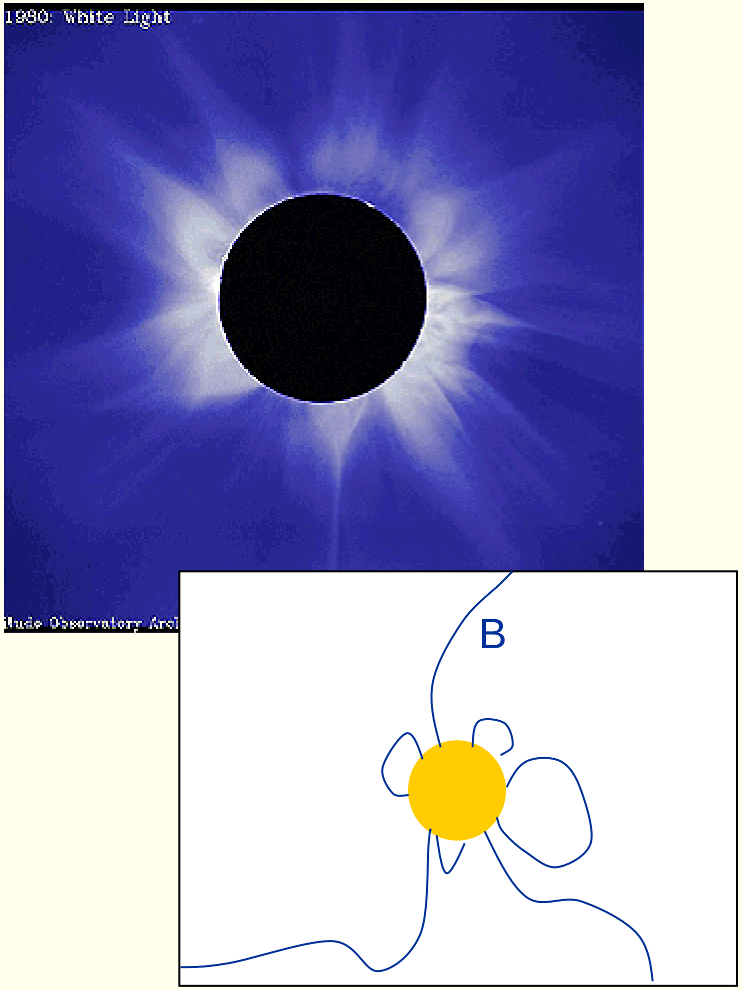


Maximum

Minimum

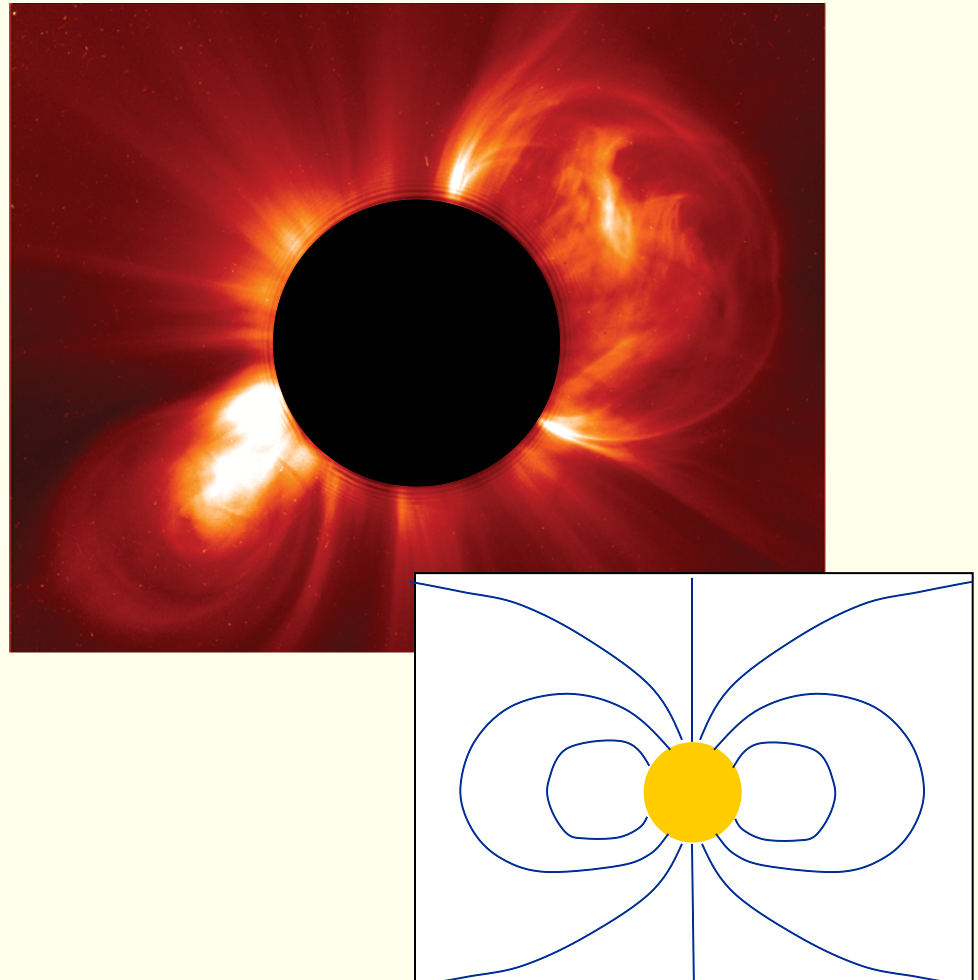
Solar magnetic field as organizing factor

Maximum



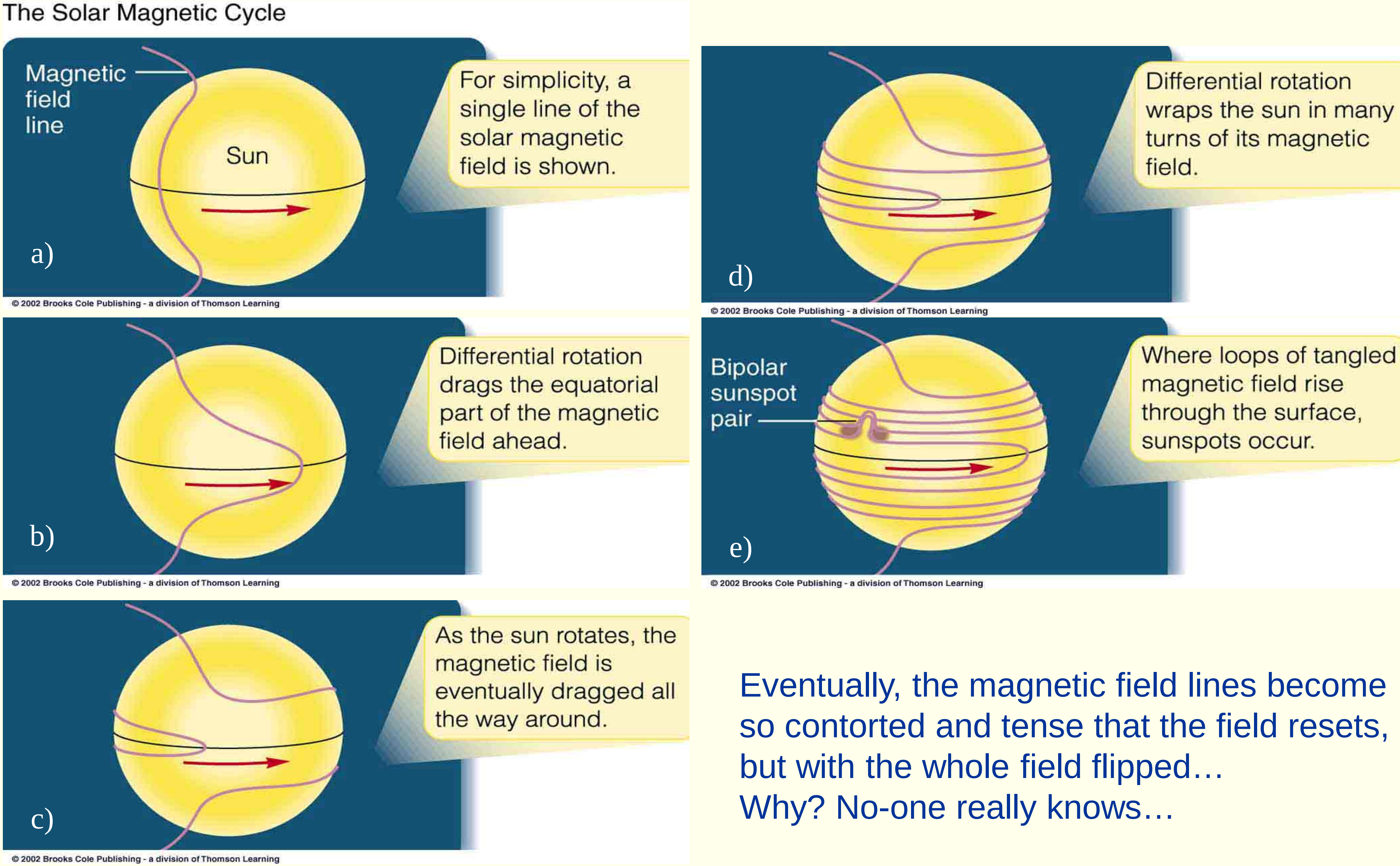
Maximum: weak, irregular magnetic field

Minimum



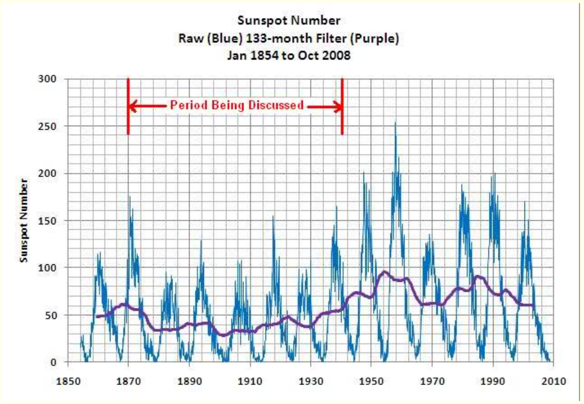
Minimum: large, regular dipole-like field

The Babcock Model

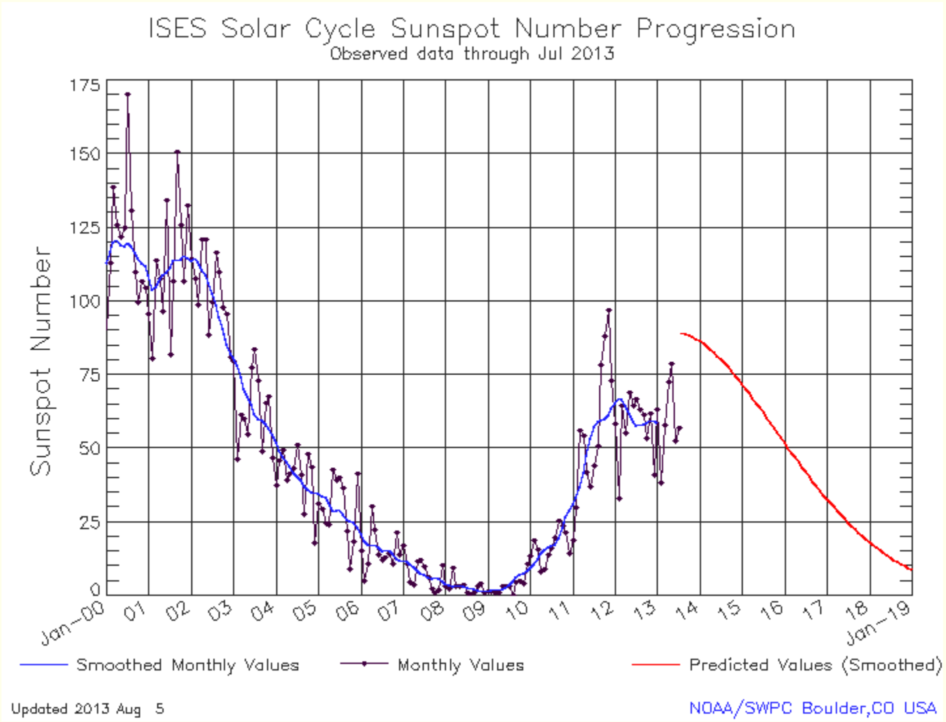


Eventually, the magnetic field lines become so contorted and tense that the field resets, but with the whole field flipped…
Why? No-one really knows…

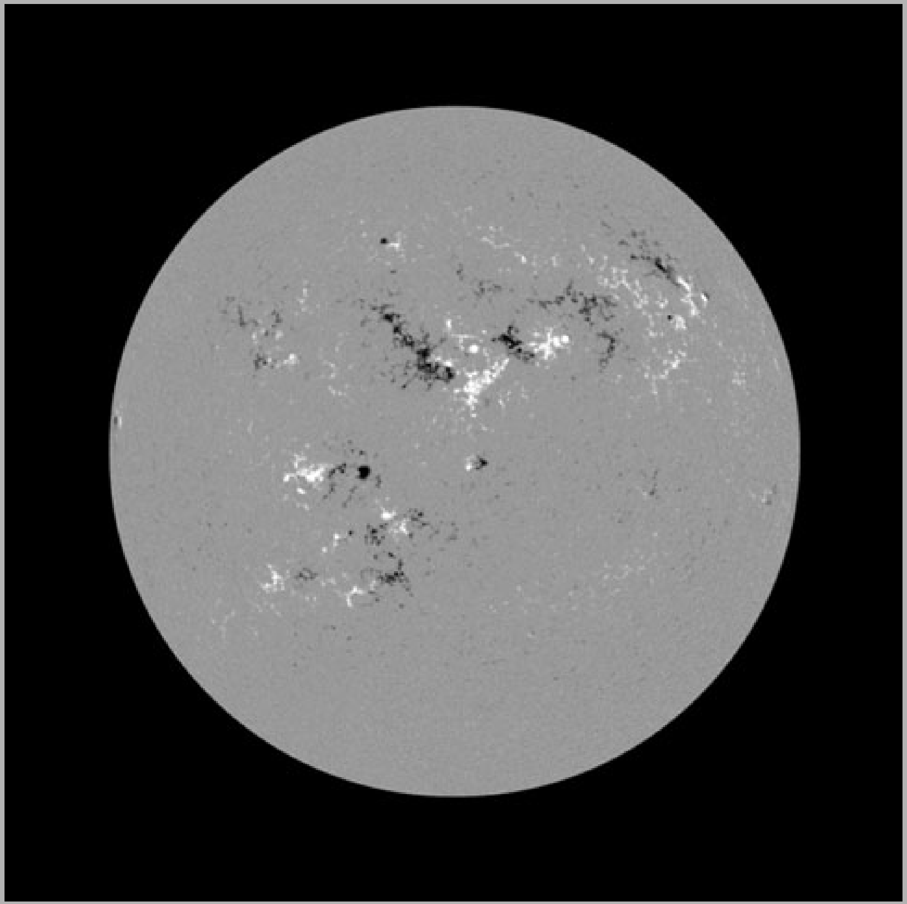
Where are we today?



Prediction by
National Weather ServiceSpace Weather Prediction Centre



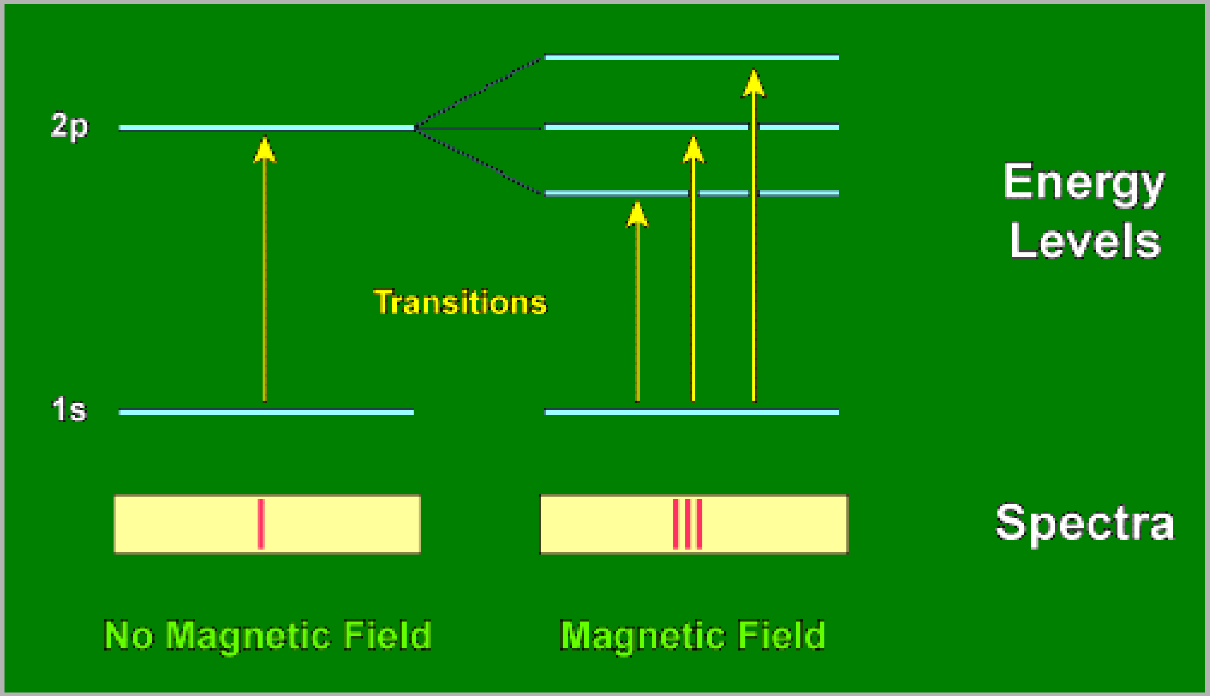
Think about this

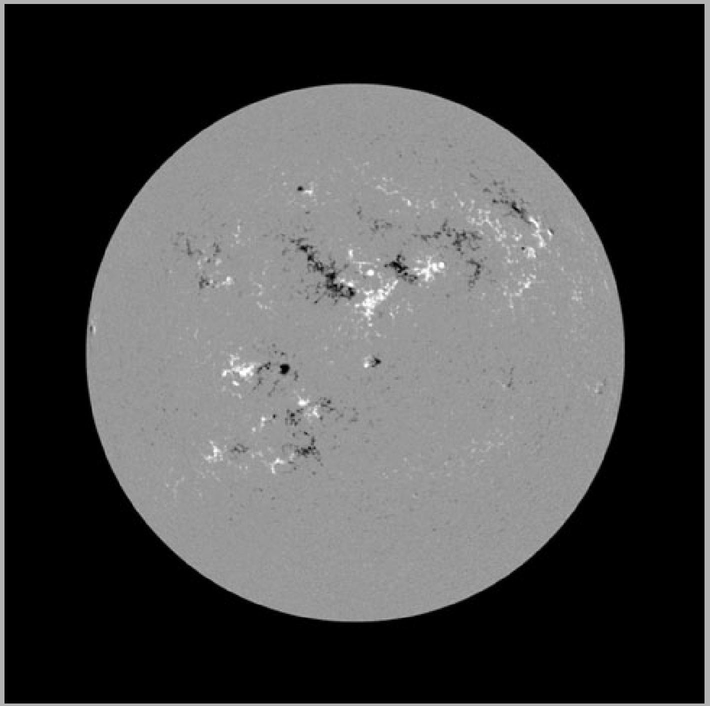


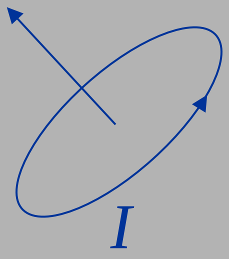
How can we measure the magnetic field on the solar surface???

Zeeman effect:

In the presence of a magnetic field electron orbits with different angular momentum will interact with B in slightly different ways. Thus the energy levels will split up. The larger B, the larger split.







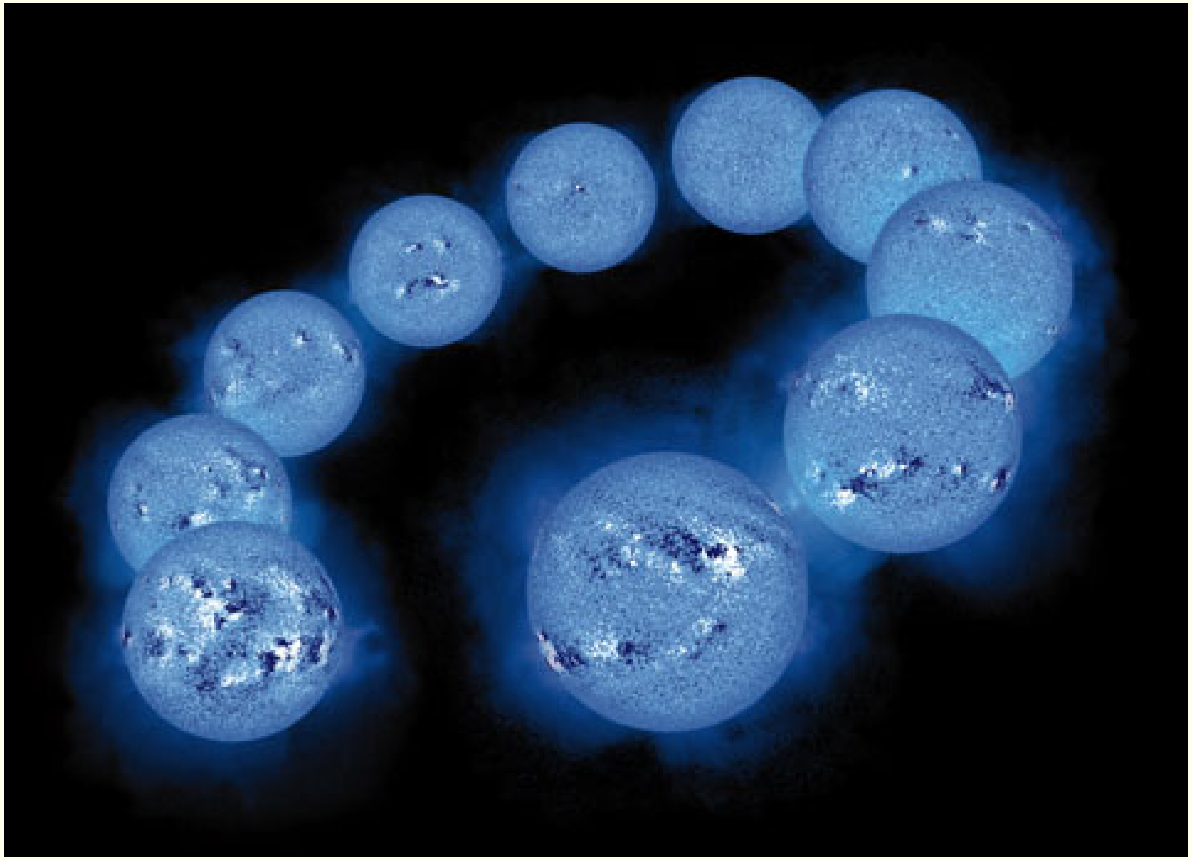
$$W = -\boldsymbol{\mu} \cdot \mathbf{B}$$

$$\mu = IA$$

Solar activity in general

On the solar surface there are various dynamical irregularities and structures.

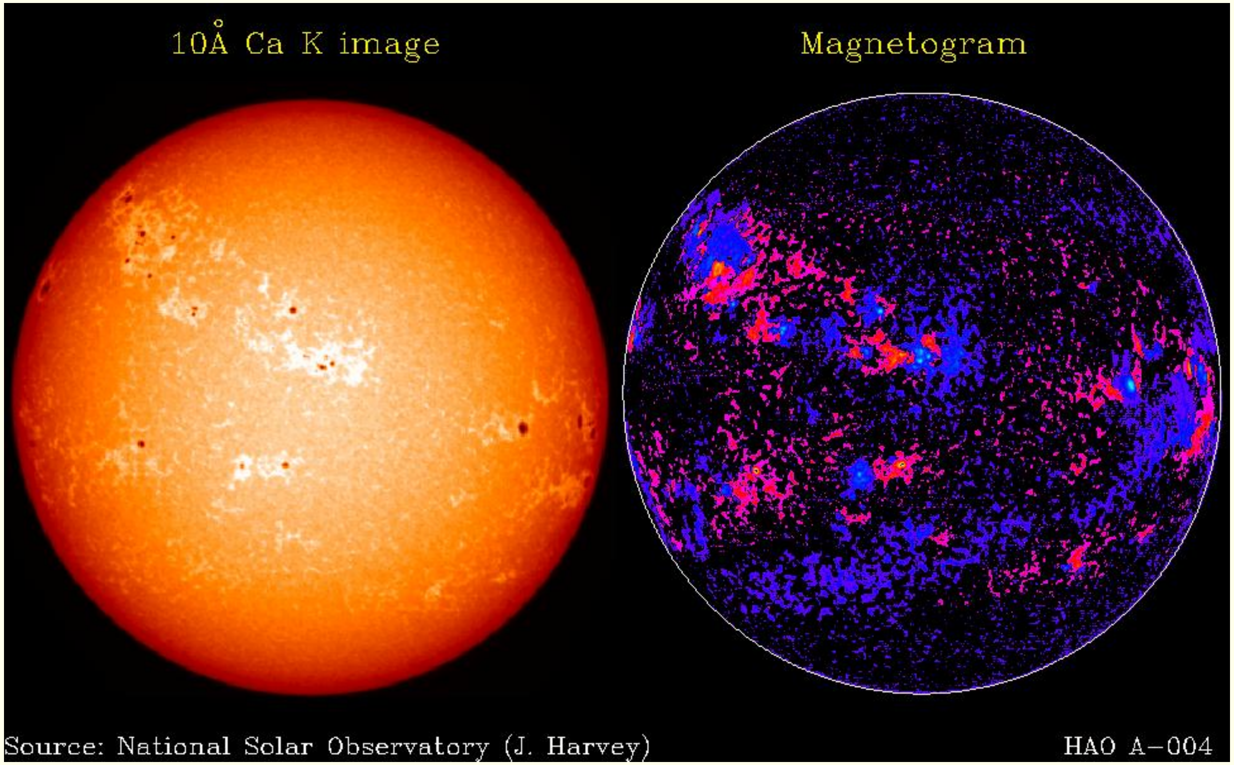
These are given the general name ”solar activity” or ”active regions”.



Magnetograms during a solar cycle

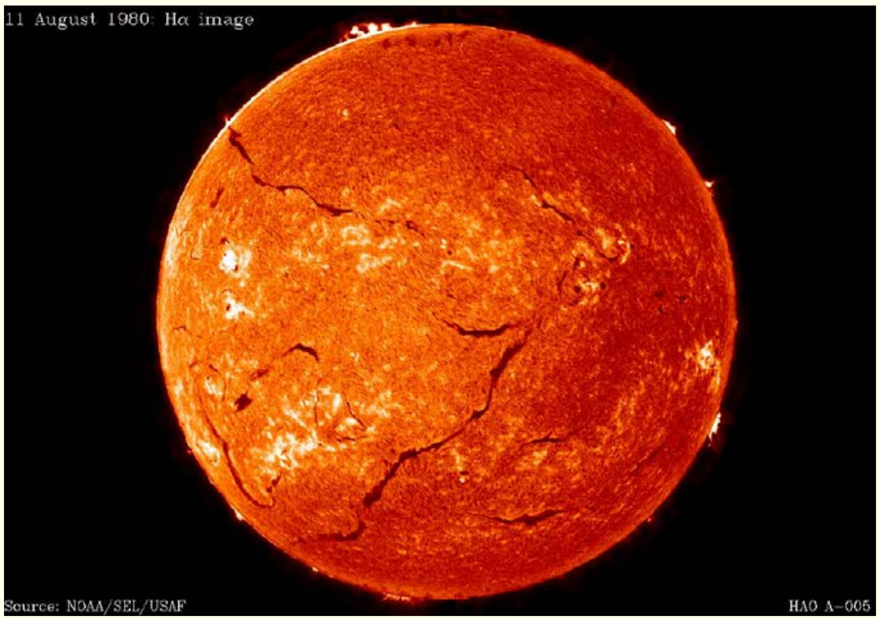
Active regions

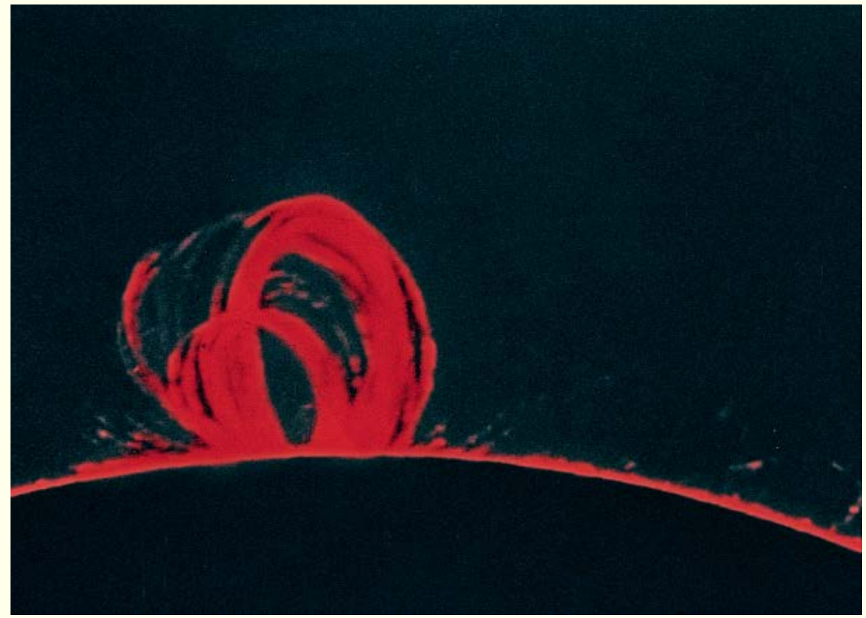
- Sunspots:
  B ~ 100 – 400 mT
- Plages:
  B ~ 10 – 50 mT
- Rest of solar surface:
  B ~ 0,1 – 0,3 mT



Prominences

When viewed from above they are called "filaments"





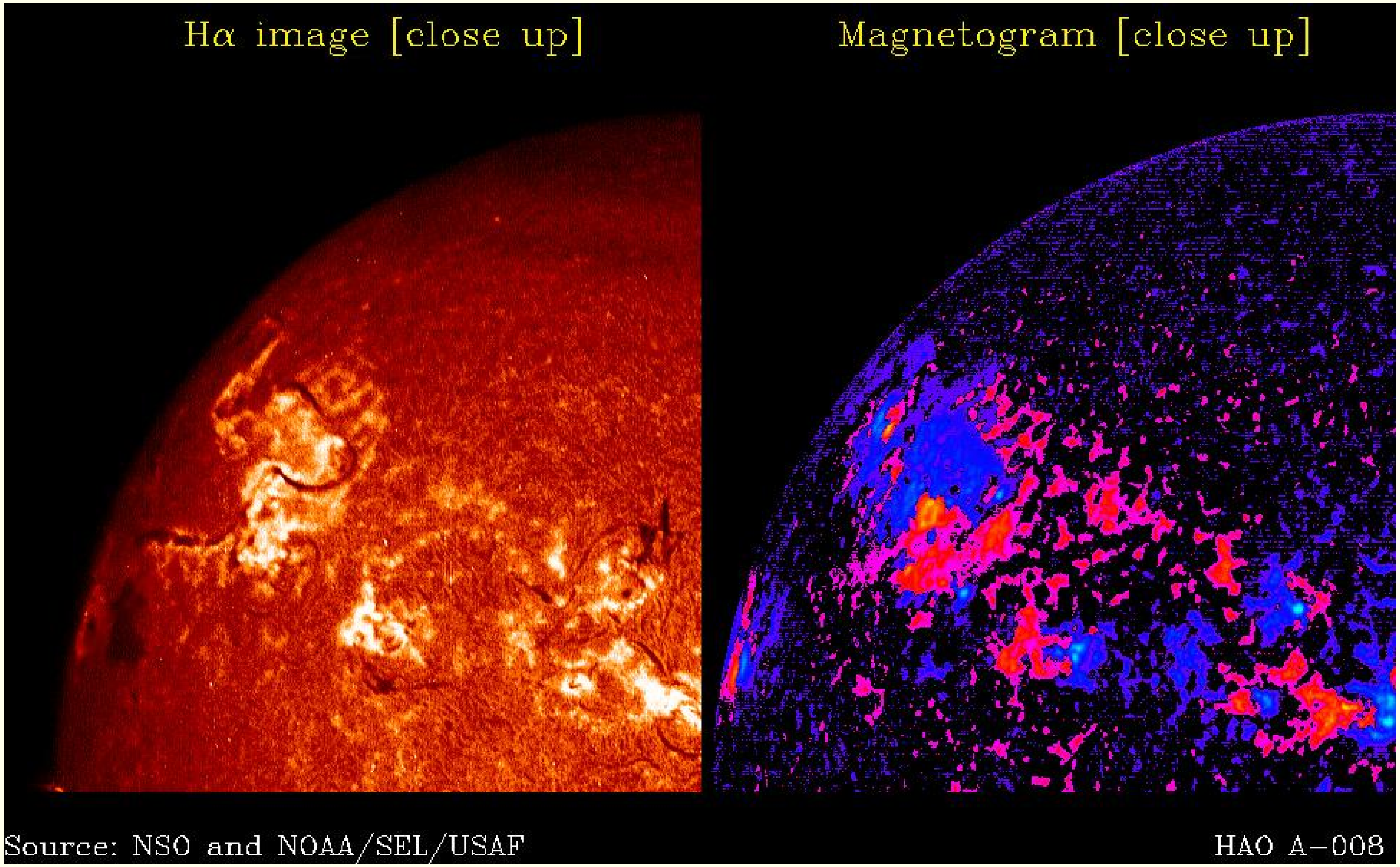
Viewed from the side: prominences

Possibly they are hotter plasma, their lower density to give them buoyancy,

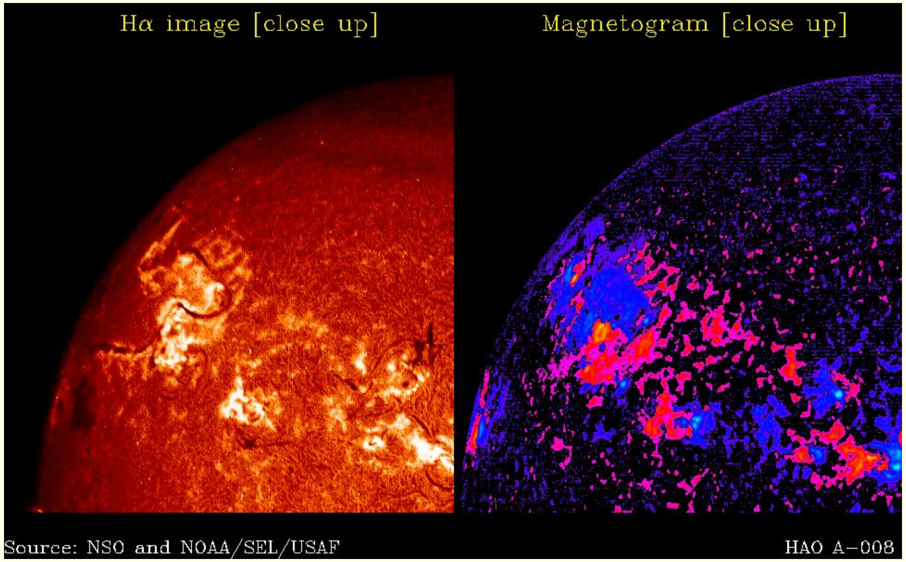
But most theories consider them to be colder material, supported by magnetic field lines.

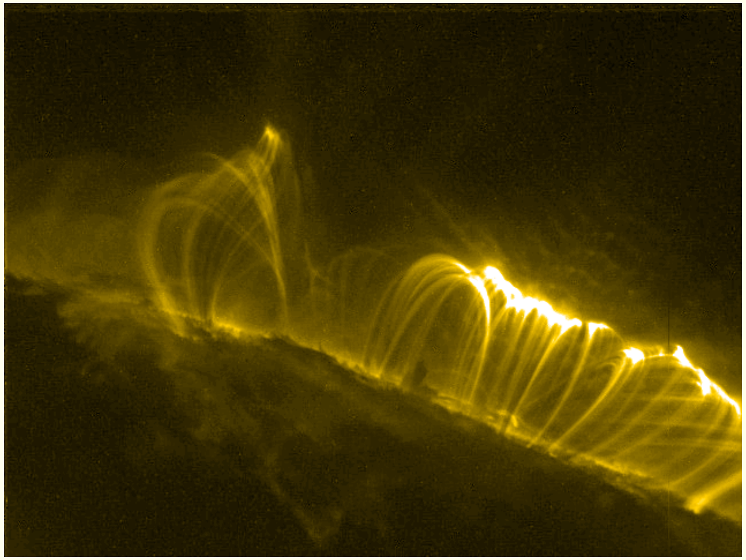
Prominences

Prominences are often observed at the border between regions of different magnetic polarity.

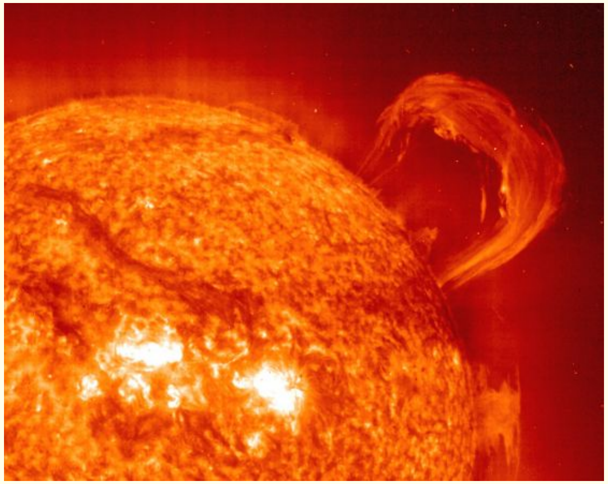


Prominences = filaments



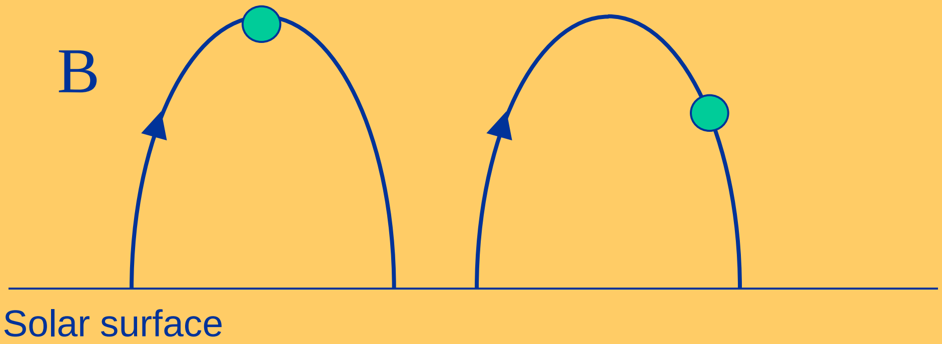


Interpretation: street of coronal loops along the border between polarities



Alternatively: one single, large loop makes up the prominence/filament.

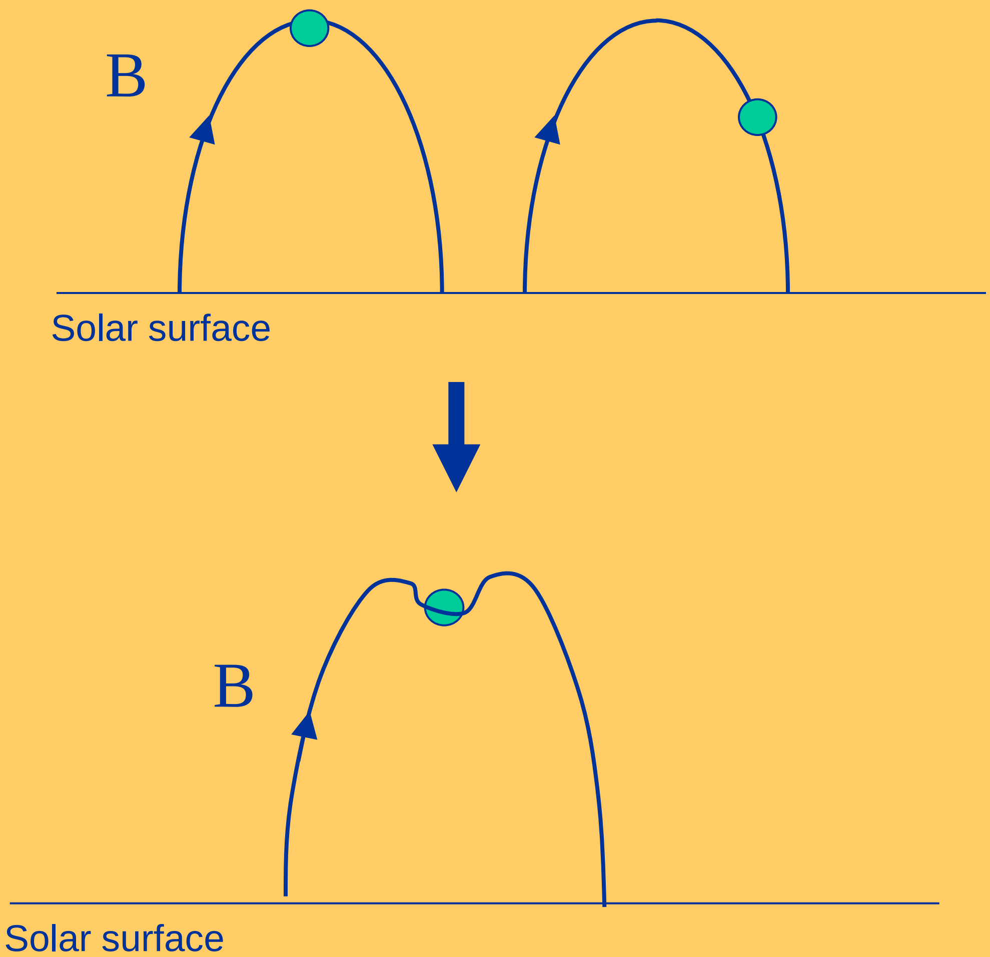
Think about this:

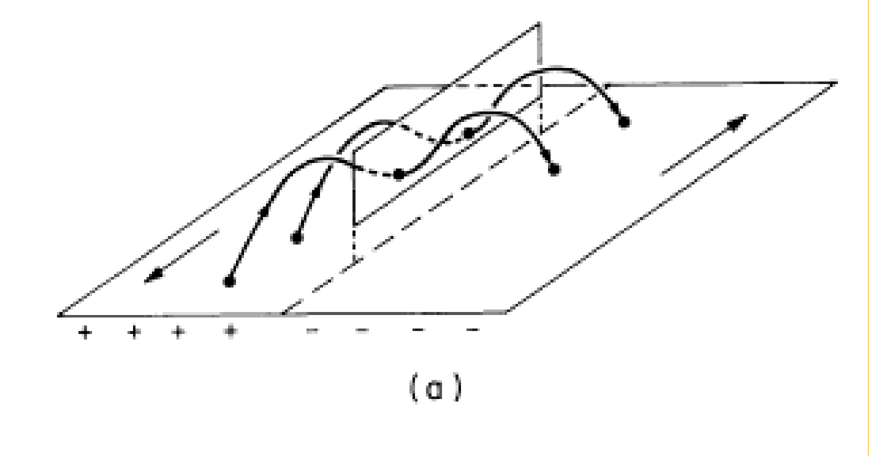


Plasma can only move along field lines. Due to gravity a plasma element at the top will ”fall down” from the top by the slightest disturbance.

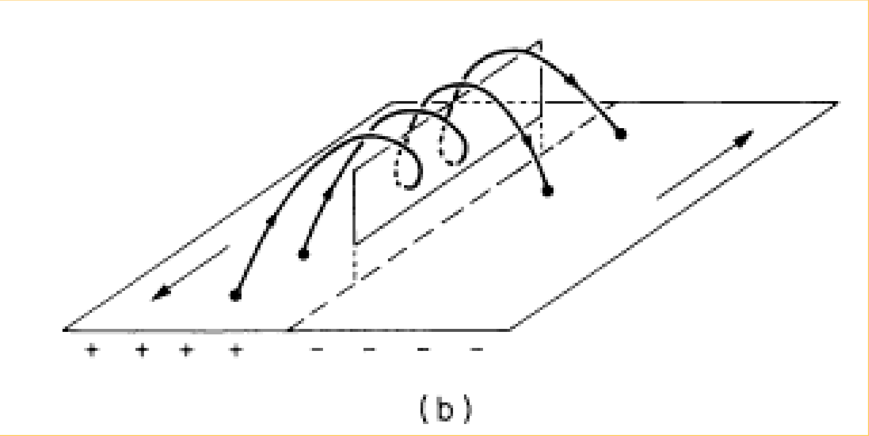
Can you think of a slight modification of the field line which may support the plasma element in a stable way?

Think about this:





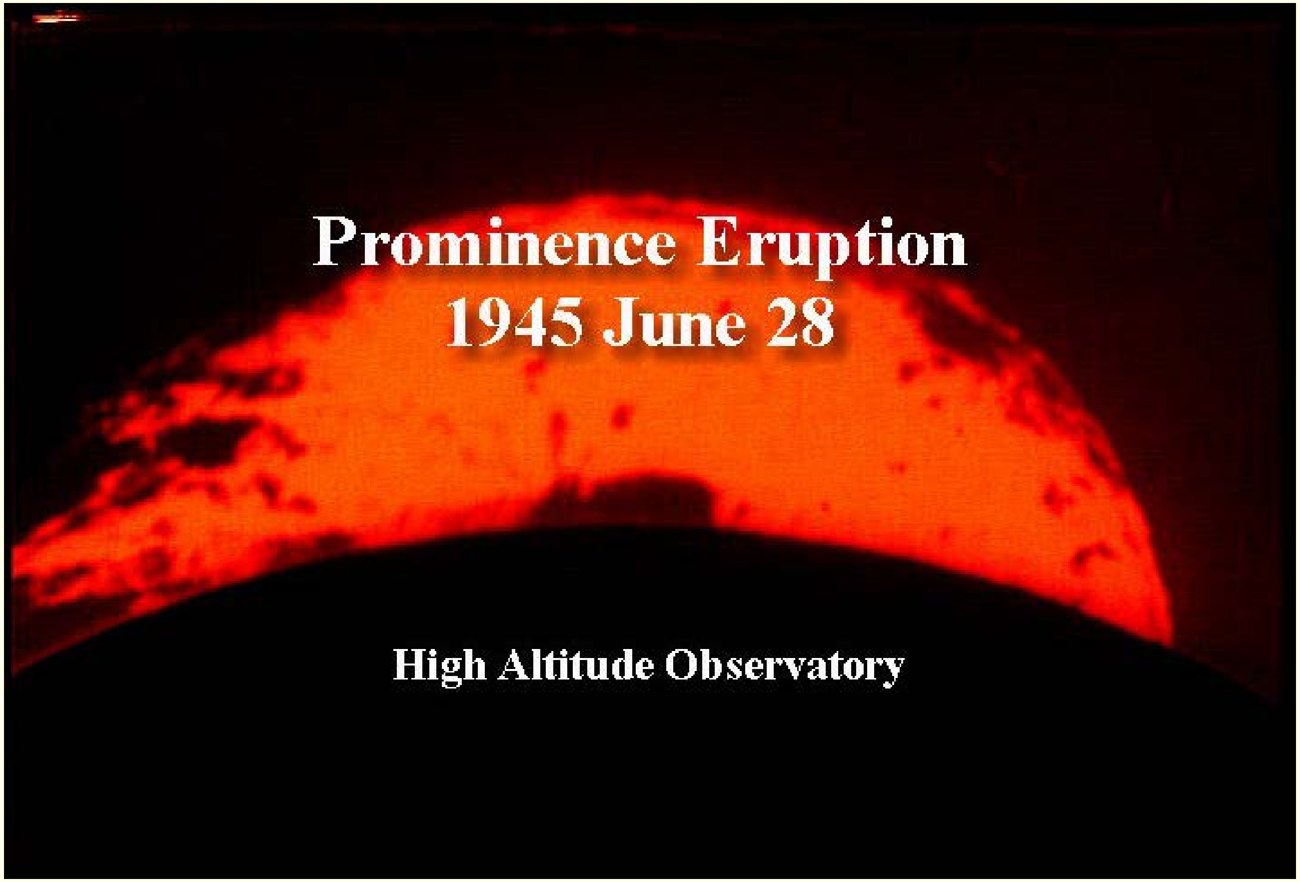
Kippenhahn-Schlüter model

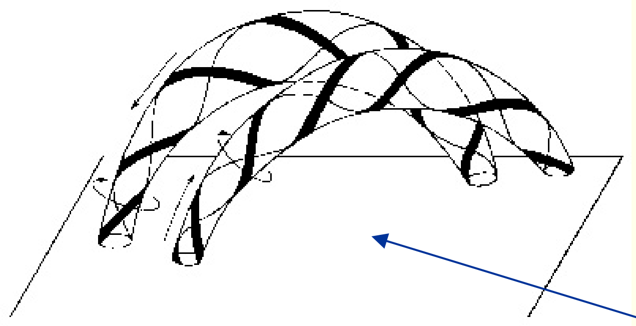


Kuperus-Raadu model

Erupting prominces

Sometimes the prominences may go unstable and release the energy stored in the magnetic fields.

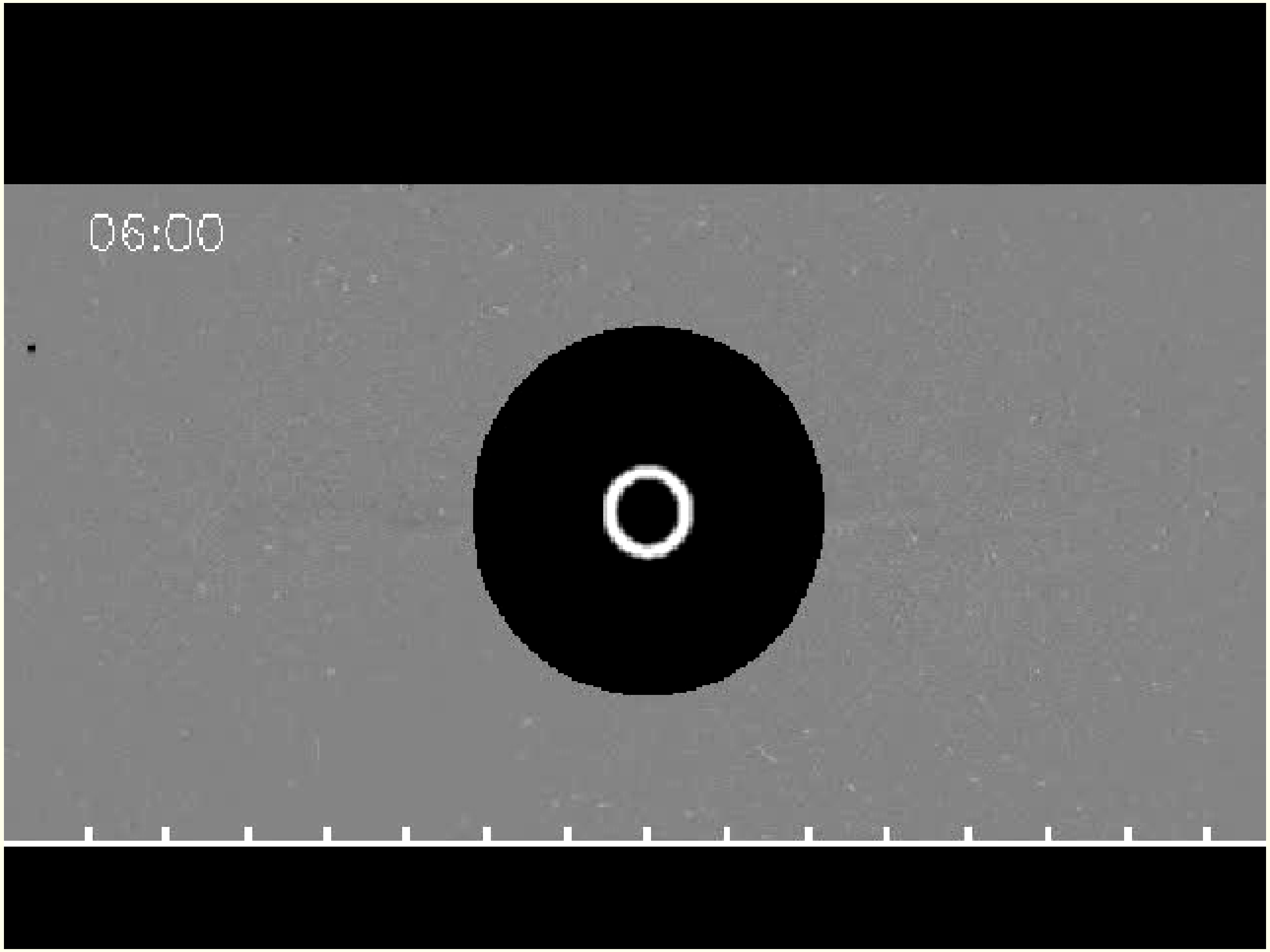




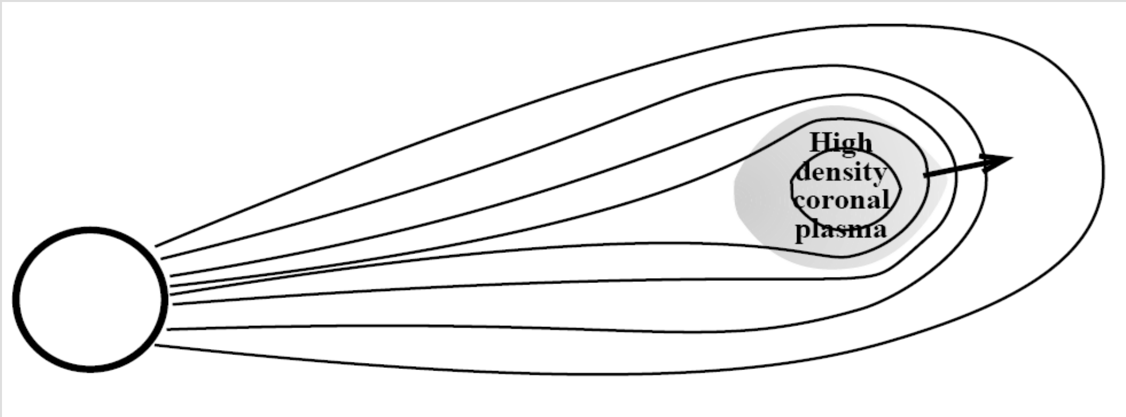
Twisted magnetic field lines store additional energy

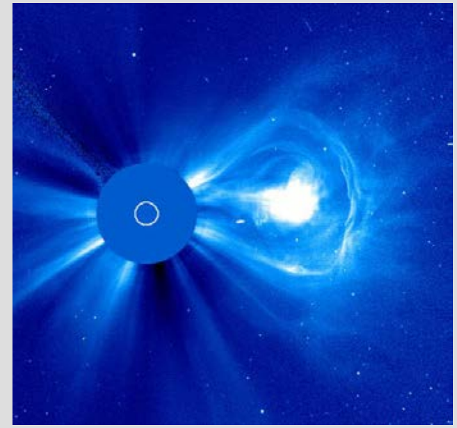
Coronal mass ejections – CME

- Often associated with ***prominences***, ***solar flares*** or "***helmet strea-mers***", but the exact mechanisms are not known
- May contain up to10^{13} kg matter
- May have velocities of up to 1000 km/s

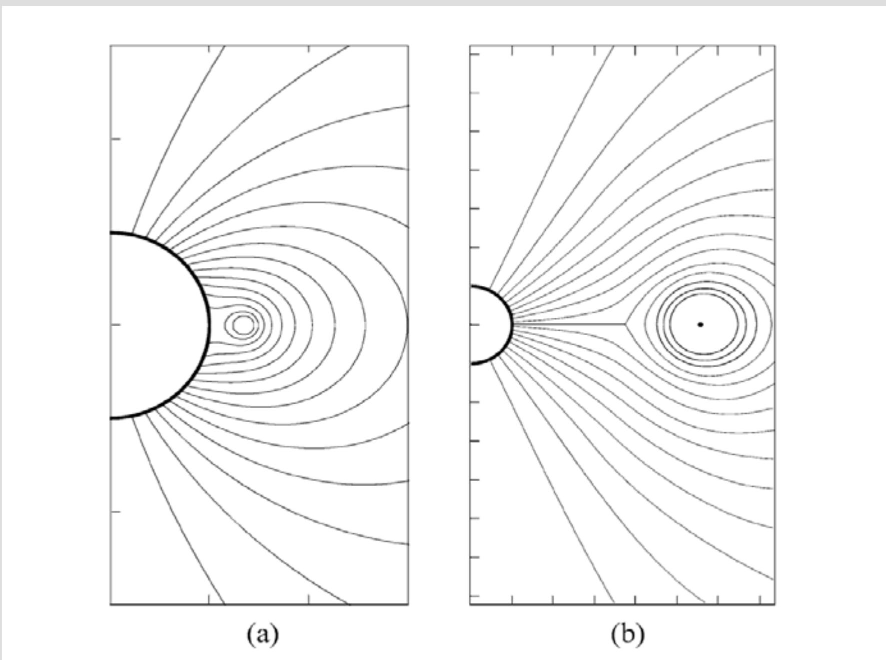


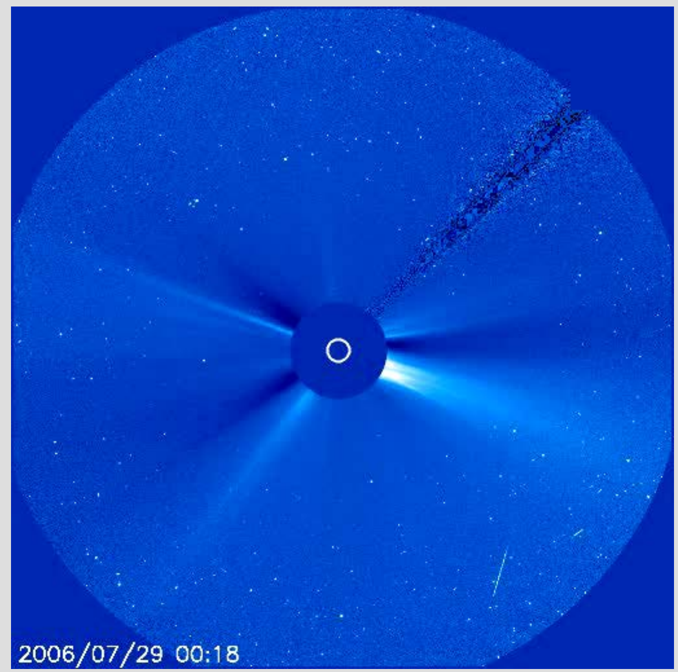
CME - magnetic connection to sun





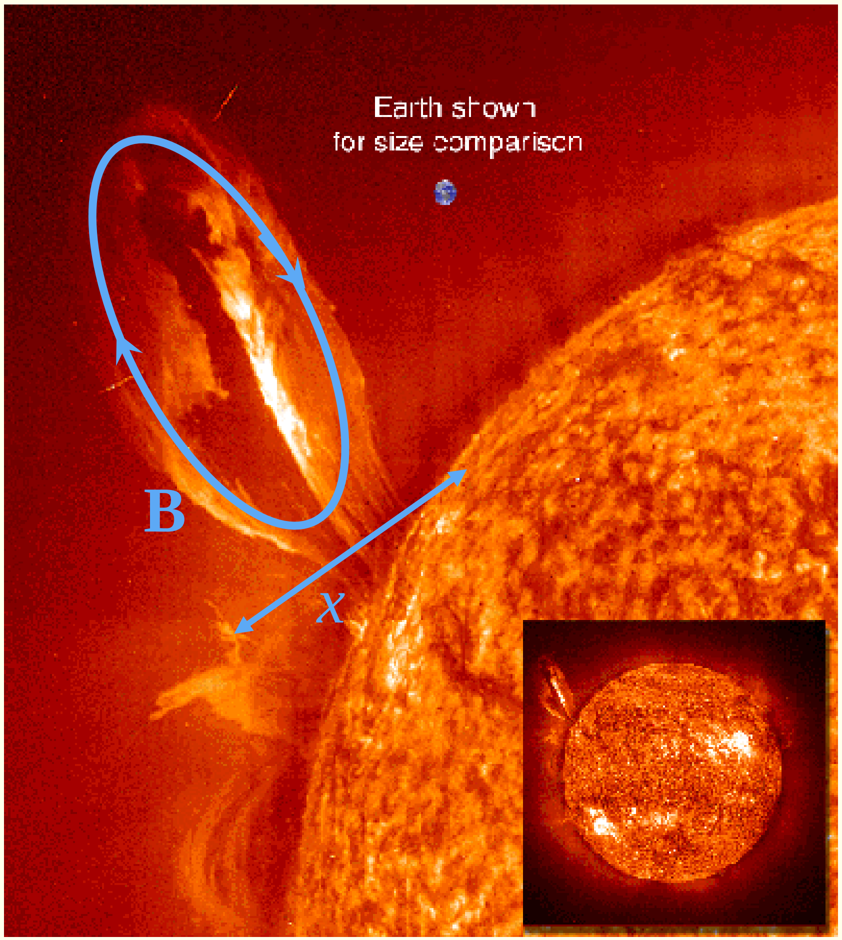
flux rope CME





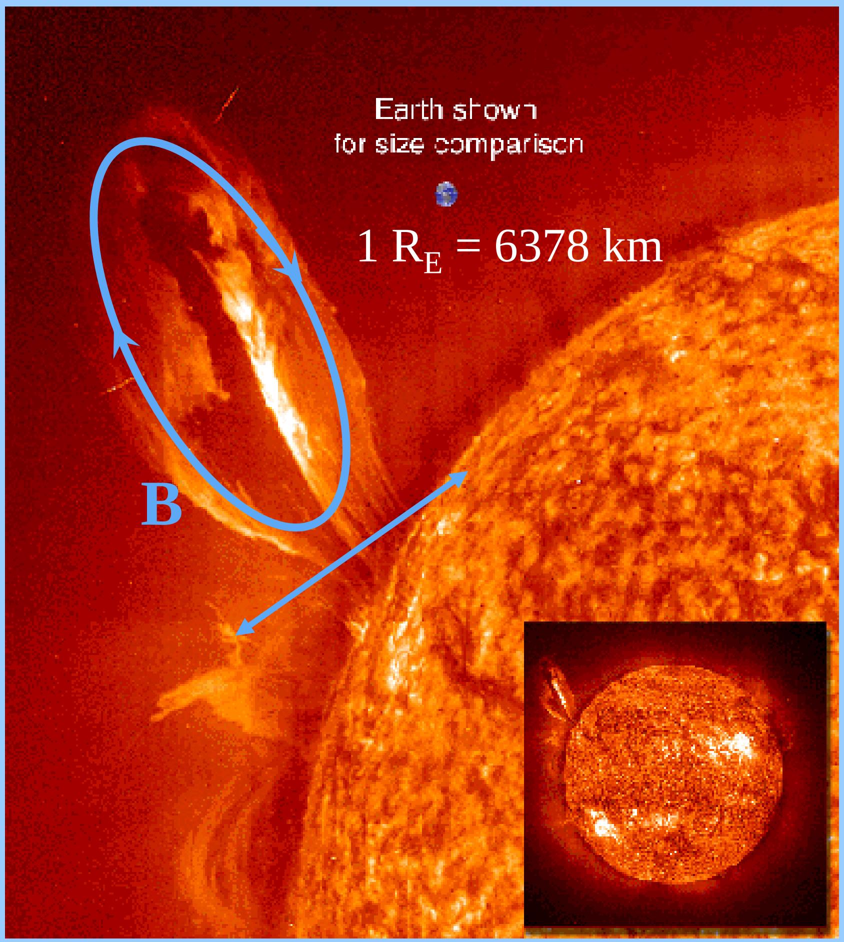
'smoke ring' CME

Coronal mass ejections



CME are sometimes called "magnetic clouds", because of their magnetic field configuration.

Coronal mass ejections



Estimate the kinetic energy of this CME!
(***Order of magnitude!***)

Suppose the density ρ of the plasma in the cloud is 1000 times denser than the plasma in the lower corona, which is $\rho \approx 10^{-18}$ kg/m^3

Suppose the CME velocity is v = 1000 km/s

Red	$W = 10^{12}$ J
Blue	$W = 10^{17}$ J
Yellow	$W = 10^{22}$ J
Green	$W = 10^{27}$ J

$r \approx 20\ \mathrm{R_E}$

$V_{CME} \approx 4\pi r^3/3 \approx 4\pi \cdot 20^3 \cdot (6378 \cdot 10^3)/3 \approx 9 \cdot 10^{24}\ \mathrm{m^3}$

$m_{CME} = V_{CME} \cdot \rho_{CME} = 9 \cdot 10^{24} \cdot 10^{-15} \approx 10^{10}\ \mathrm{kg}$

Maybe the cloud is not fully filled with matter, but I will assume that that is a relatively small correction.

$W_{CME} = m_{CME} v_{CME}^2 = 10^{10} \cdot (1000 \cdot 10^3)^2 \approx 10^{22}\ \mathrm{J}$

Yellow $W_{CME} = 10^{22}\ \mathrm{J}$

C.f. nuclear reactor: $P \approx 1$ GW.
In one year: $W \approx 10^{16}$ J

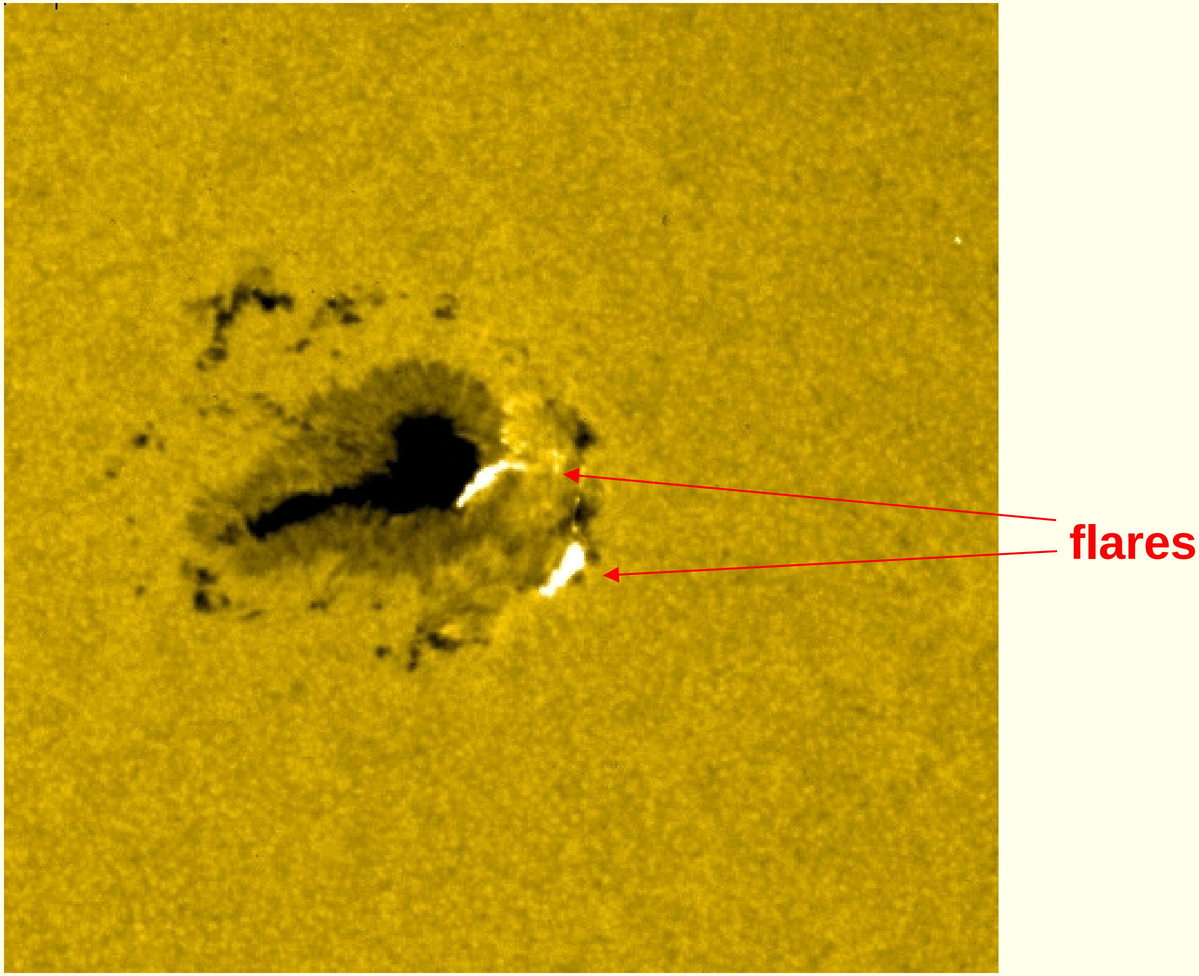
Solar flare

1972, August 07, Big Bear Solar Observatory

- Solar flares are explosive intensifications in X-ray, UV and visible light.
- Intensification in X-ray may be up to a factor 10^4
- Last for ~ 1 – 60 min.

Solar flares

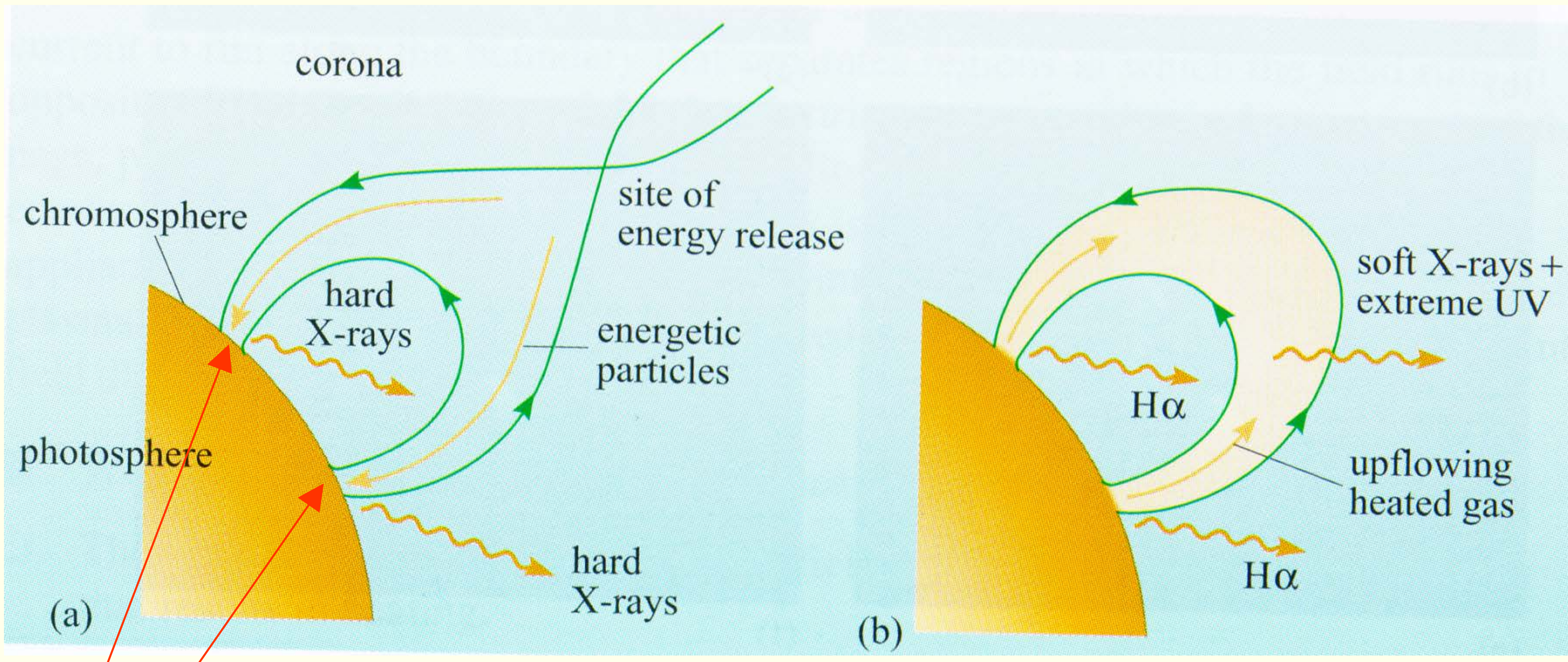
Size of solar flares is comparable to sunpots.



Solar flare

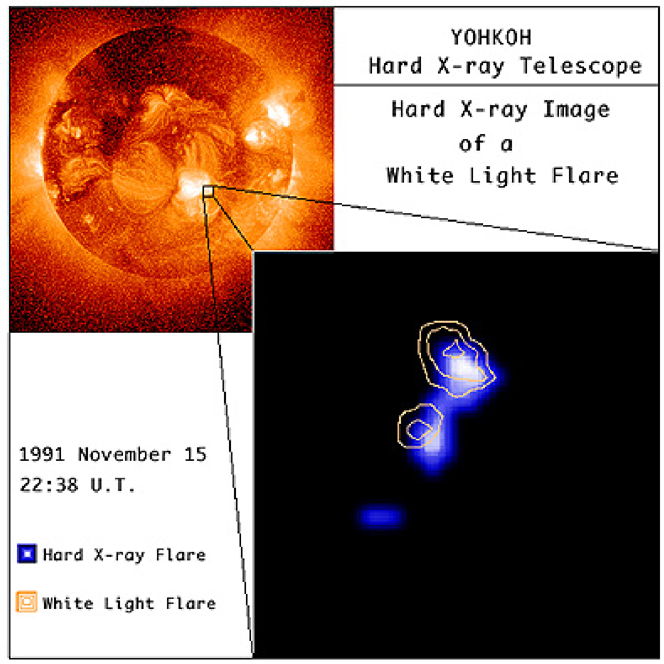

POST-FLARE LOOPS
H-alpha Observations from LaPalma
June 26, 1992
08:10 - 08:55 UT

Solar flare mechanism

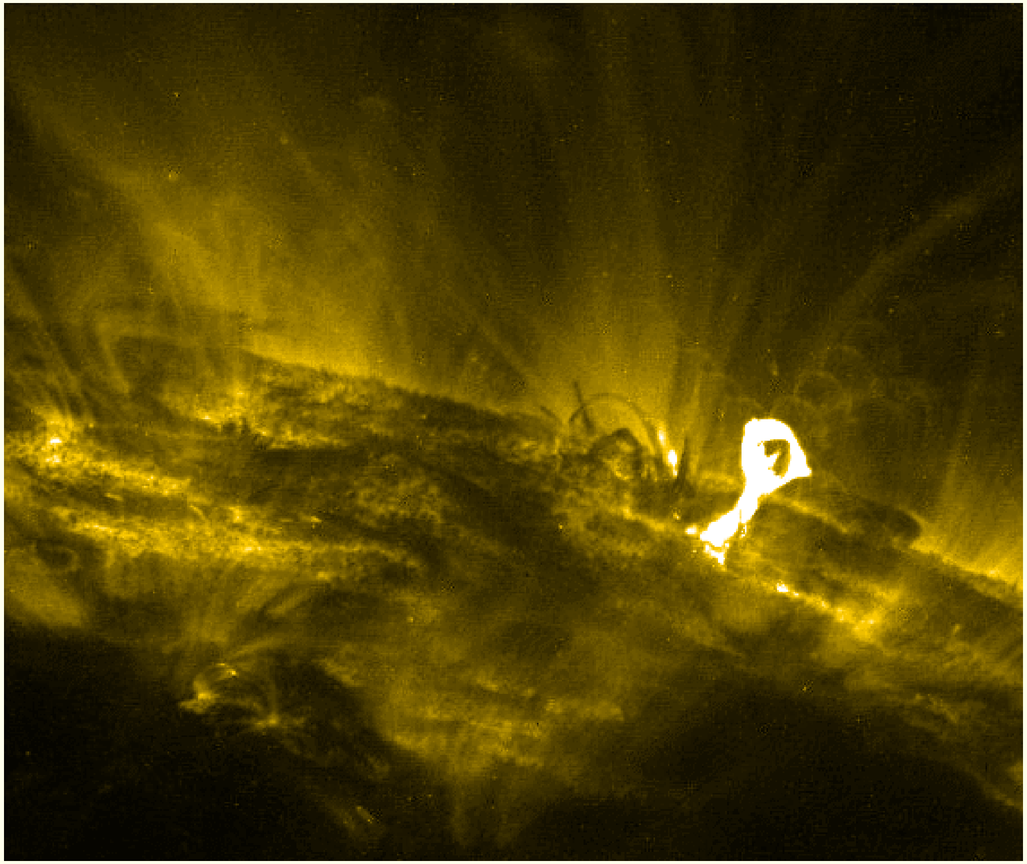


Electrons are accelerated, collide with solar surface (photosphere) and emit bremsstrahlung (X-rays).

Solar flare observations

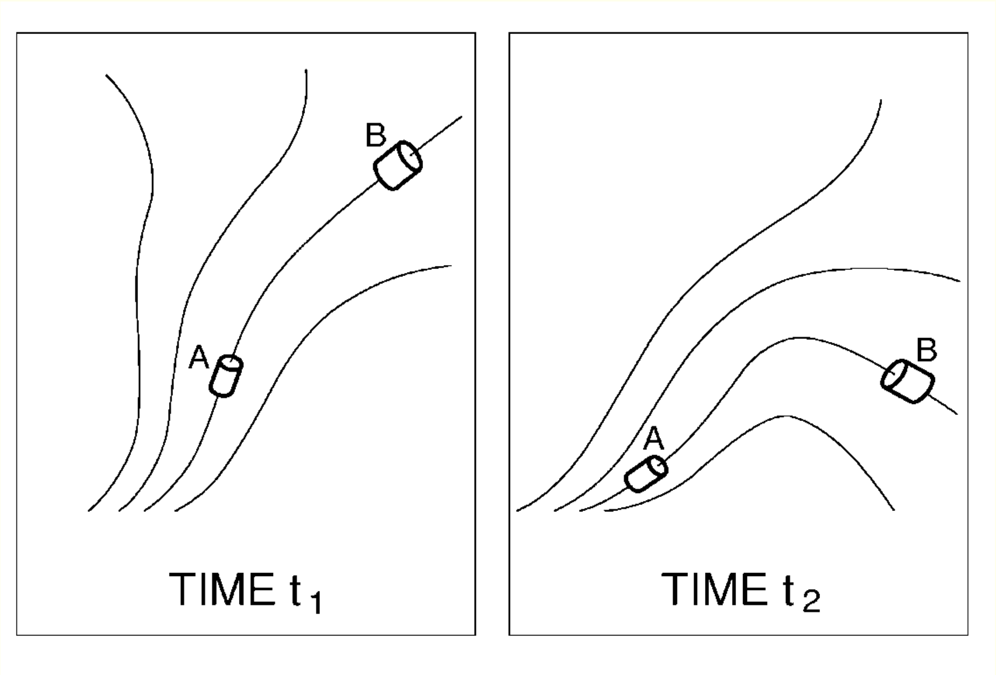


(a) double signature of x-ray emissions at foot of flare



(b) coronal loop filled with hot gas

Frozen in magnetic field lines



In fluid description of plasma two plasma elements that are connected by a common magnetic field line at time t_1 will be so at any other time t_2.

This applies if the magnetic Reynolds number is large:

$$R_m = \mu_0 \sigma l_c v_c >> 1$$

An example of the collective behaviour of plasmas.

Frozen in magnetic flux *PROOF II*

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{v} \times \mathbf{B})}_{A} + \underbrace{\frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}}_{B}$$

Order of magnitude estimate:

$$\frac{A}{B} = \frac{\nabla \times (\mathbf{v} \times \mathbf{B})}{\dfrac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}} \approx \frac{\dfrac{v \Delta B}{L}}{\dfrac{\Delta B}{\mu_0 \sigma L^2}} = v L \mu_0 \sigma \equiv R_m$$

Magnetic Reynolds number R_m:

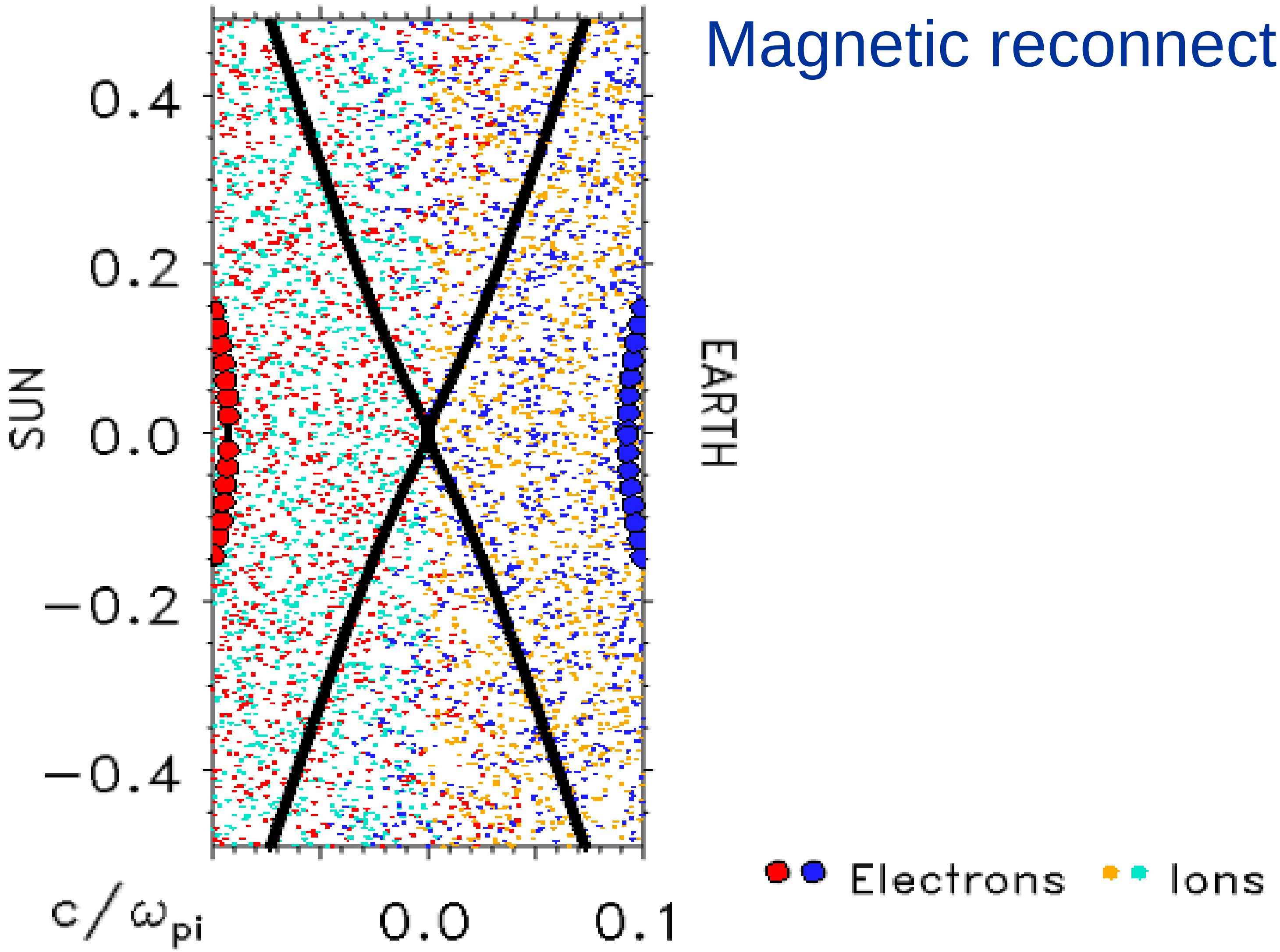
$$\mathrm{R_m} >> 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Frozen-in fields!

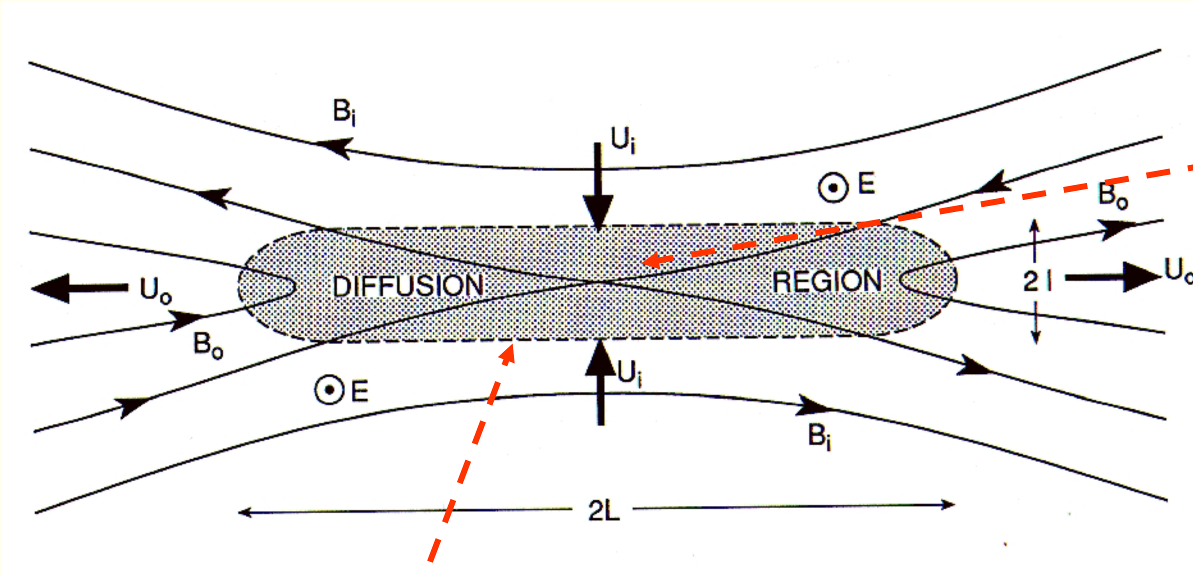
$$\mathrm{R_m} << 1 \Rightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

Diffusion equation!

Magnetic reconnection



Reconnection



In ‘diffusion region’:

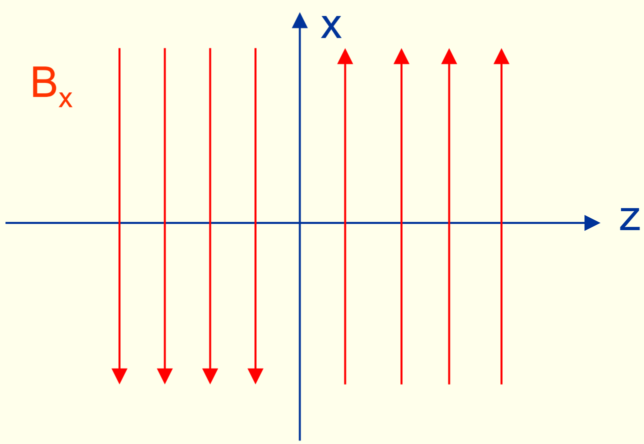
$R_m = \mu_0 \sigma l v \sim 1$

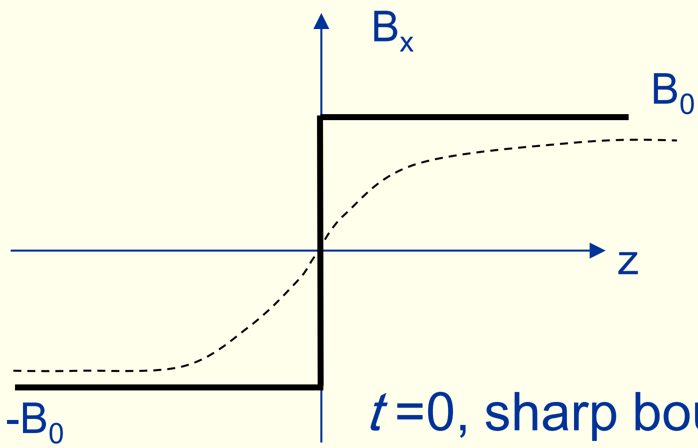
Thus: condition for frozen-in magnetic field breaks down.

A second condition is that there are two regions of magnetic field pointing in *opposite* direction:

- Field lines are “cut” and can be re-connected to other field lines
- **Magnetic energy is transformed into kinetic energy ($U_o >> U_i$)**
- **Plasma from different field lines can mix**

Reconnection in 1D





t =0, sharp boundary

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B} \longrightarrow \frac{\partial B_x}{\partial t} = \frac{1}{\mu_0 \sigma} \frac{\partial^2 B_x}{\partial z^2}$$

Diffusion equation! Has solution

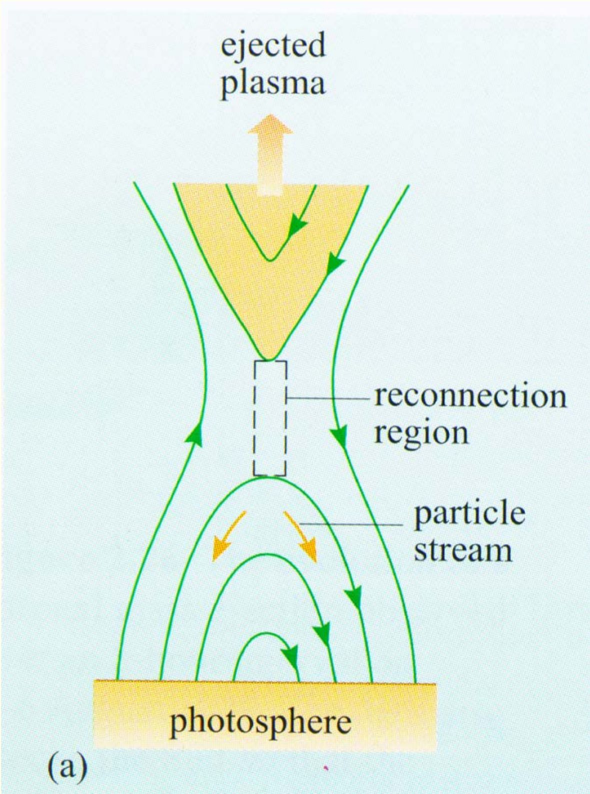
$$B_x(z,t) = B_0 erf\left(\left[\frac{\mu_0 \sigma}{4t} \right]^{1/2} z \right)$$

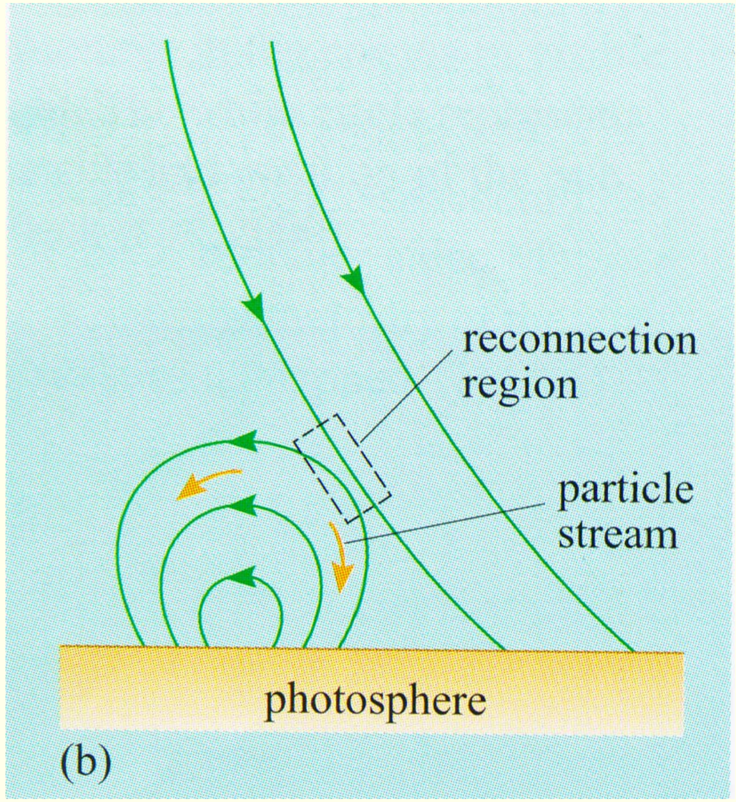
The total magnetic energy then decreases with time:

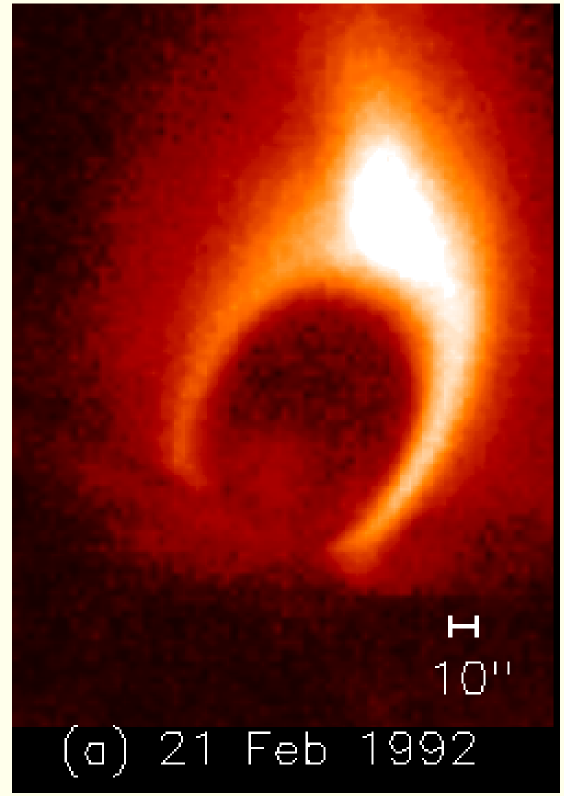
$$W_B = \int_{-\infty}^{\infty} \frac{B^2}{2\mu_0} dxdydz$$

The magnetic energy is converted into heat and kinetic energy in 2D

Solar flare
energization mechanism







Two possible reconnection geometries

Classification of flares

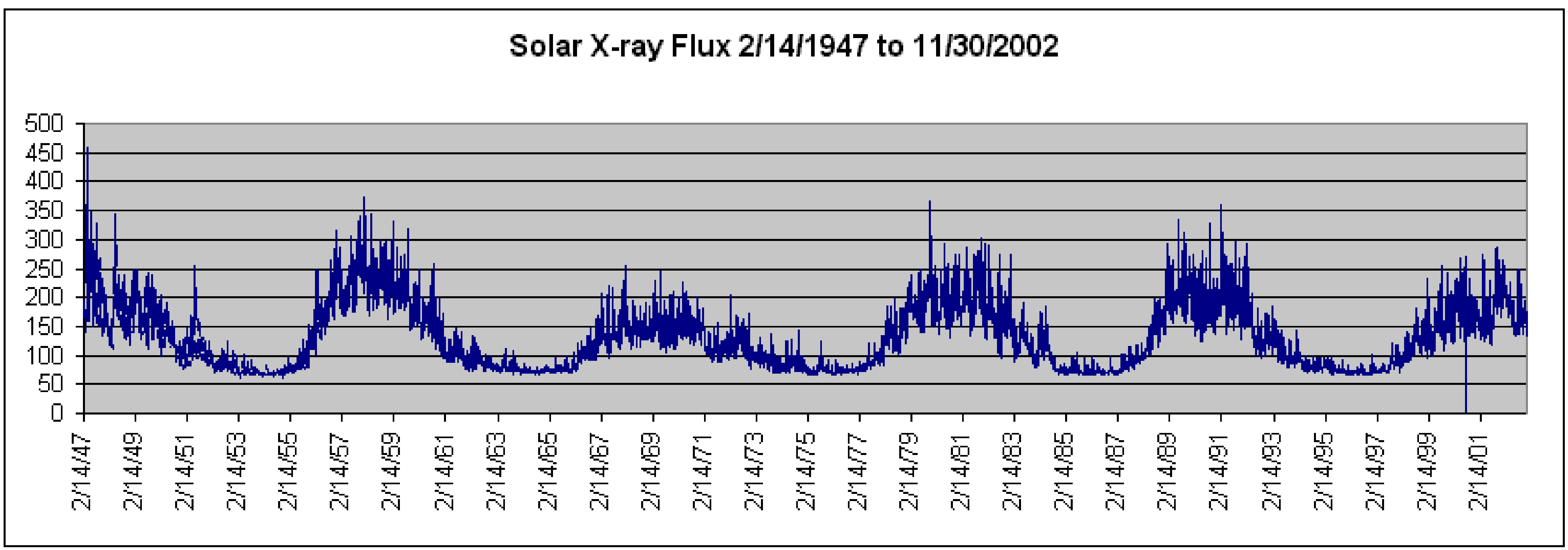
Old system

Denomination	Area $(°)^2$
S	< 2.0
1	2.1 – 5.1
2	5.2 – 12.4
3	12.5-24.7
4	> 24.7

New system

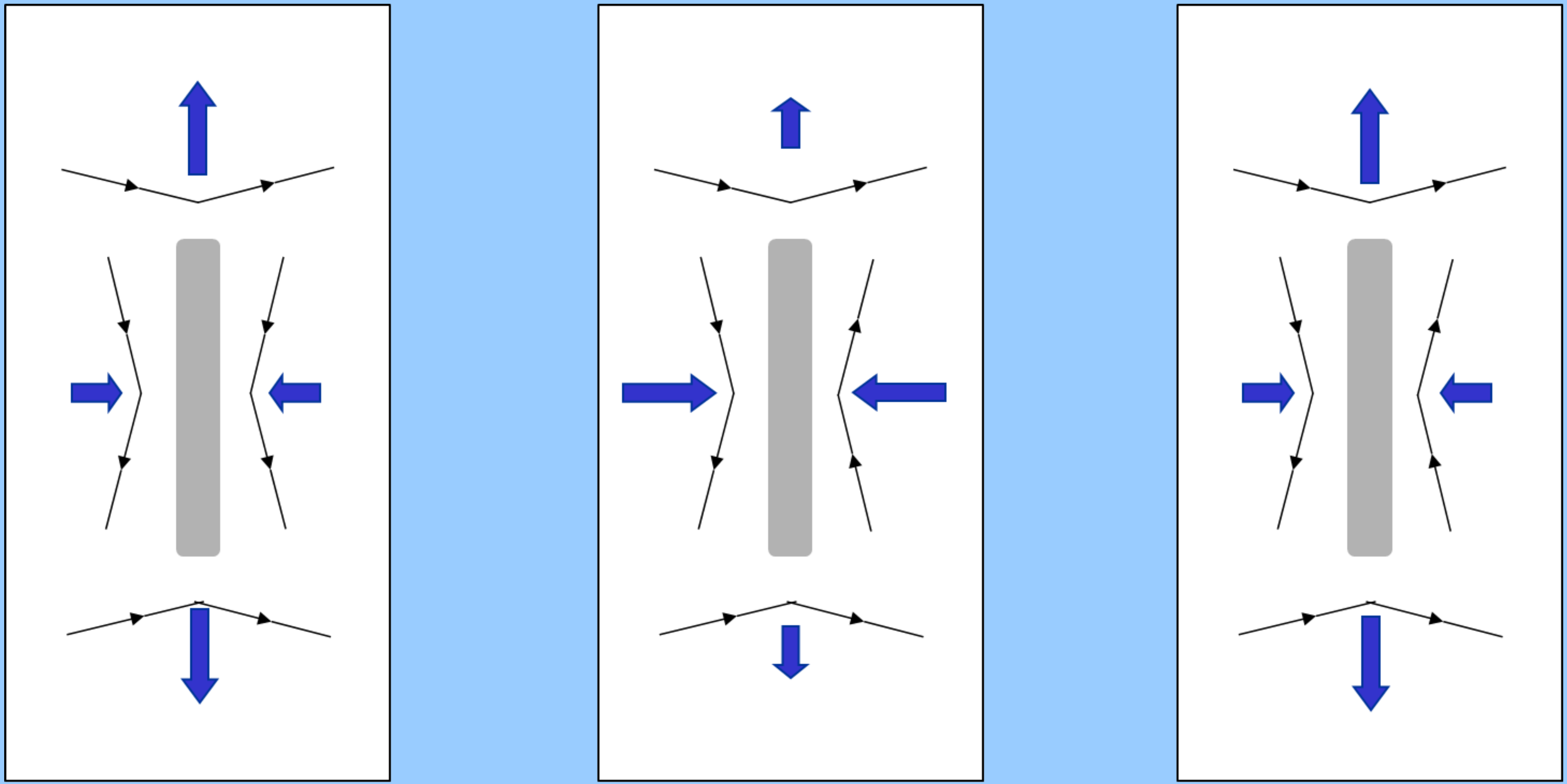
Denomination	Maximum flux of X-ray radiation (W/m^2) (near Earth 0.1-0.8 nm)
A*n*	$n \times 10^{-8}$
B*n*	$n \times 10^{-7}$
C*n*	$n \times 10^{-6}$
M*n*	$n \times 10^{-5}$
X*n*	$n \times 10^{-4}$

Recent X ray flux measurements



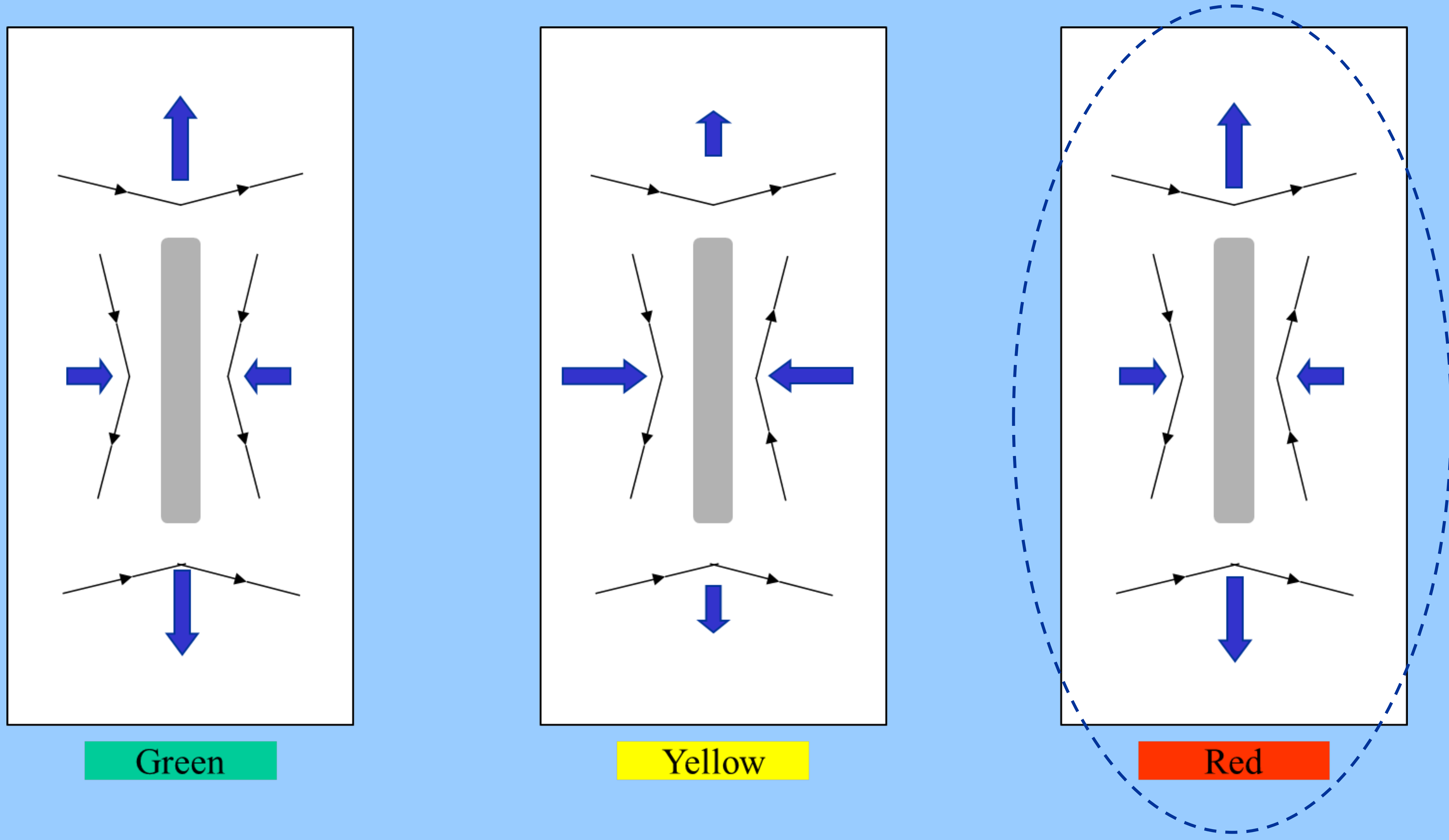
http://www.swpc.noaa.gov/ Space Weather Prediction Centre

Magnetic reconnection



Green Yellow Red

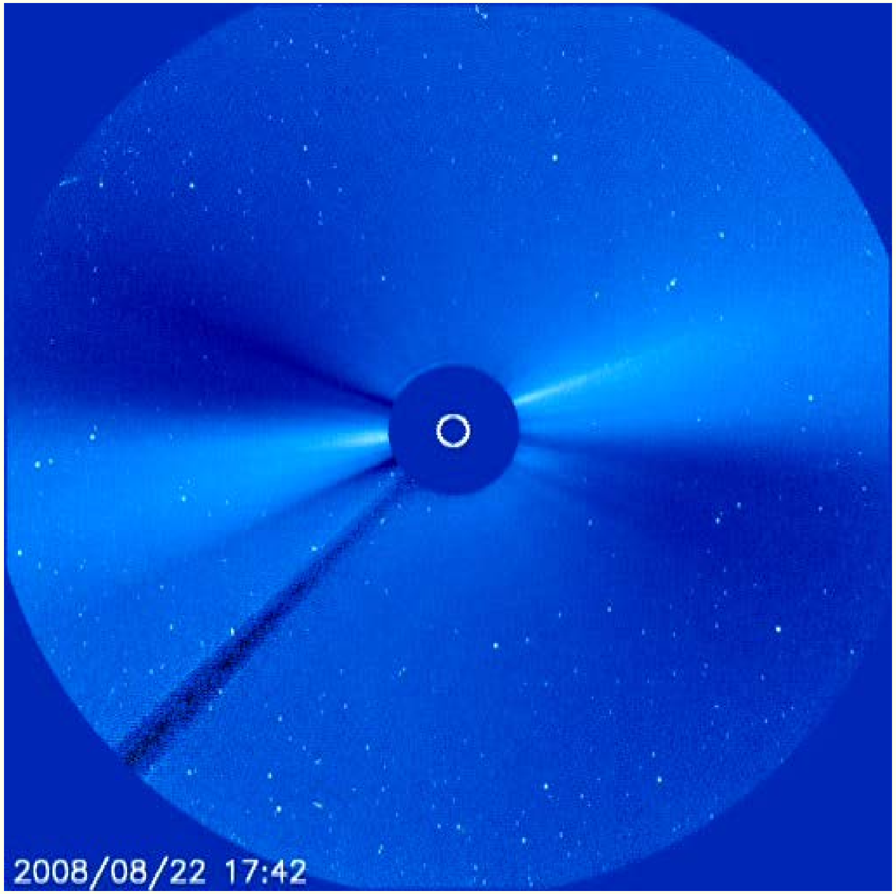
Magnetic reconnection



Think about this:

What determines the form of the spiral of the water from a rotating lawn sprinkler?

Solar wind

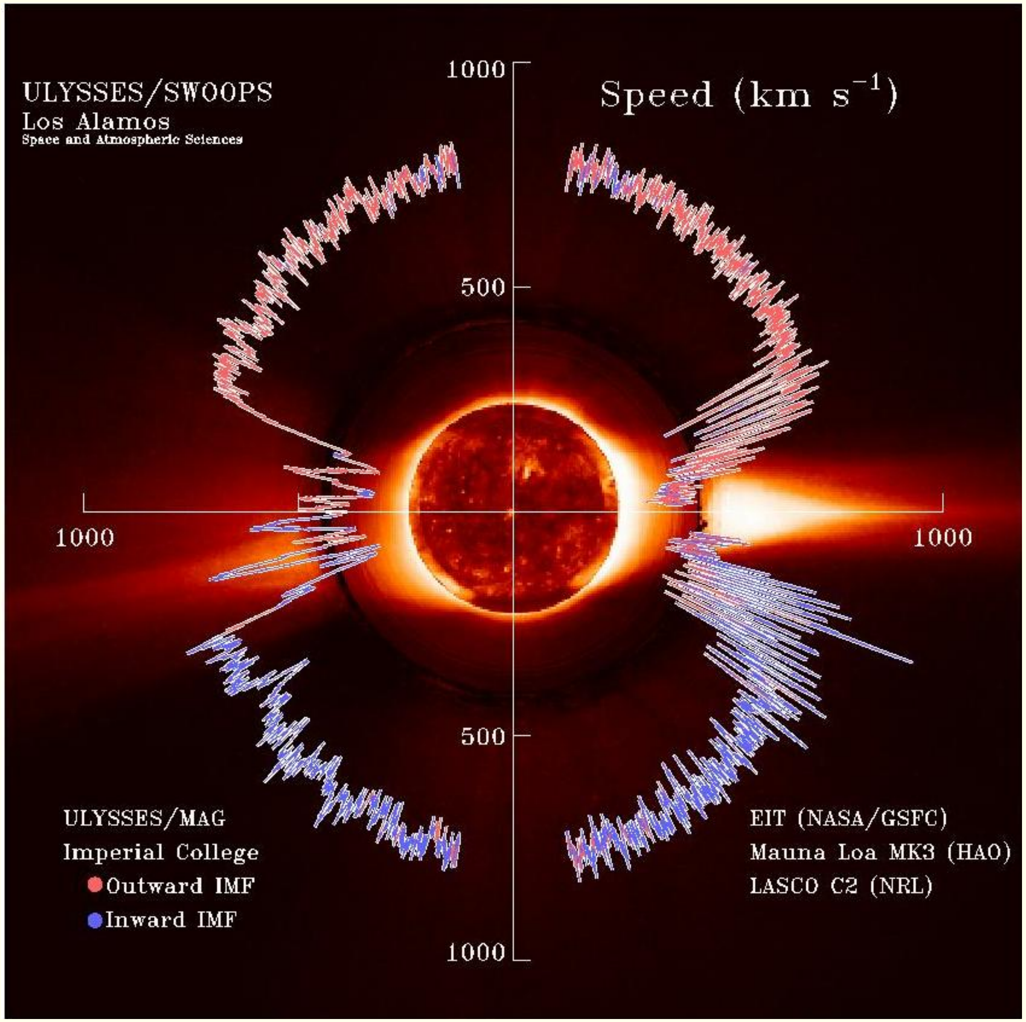


Corona continuously merges into solar wind

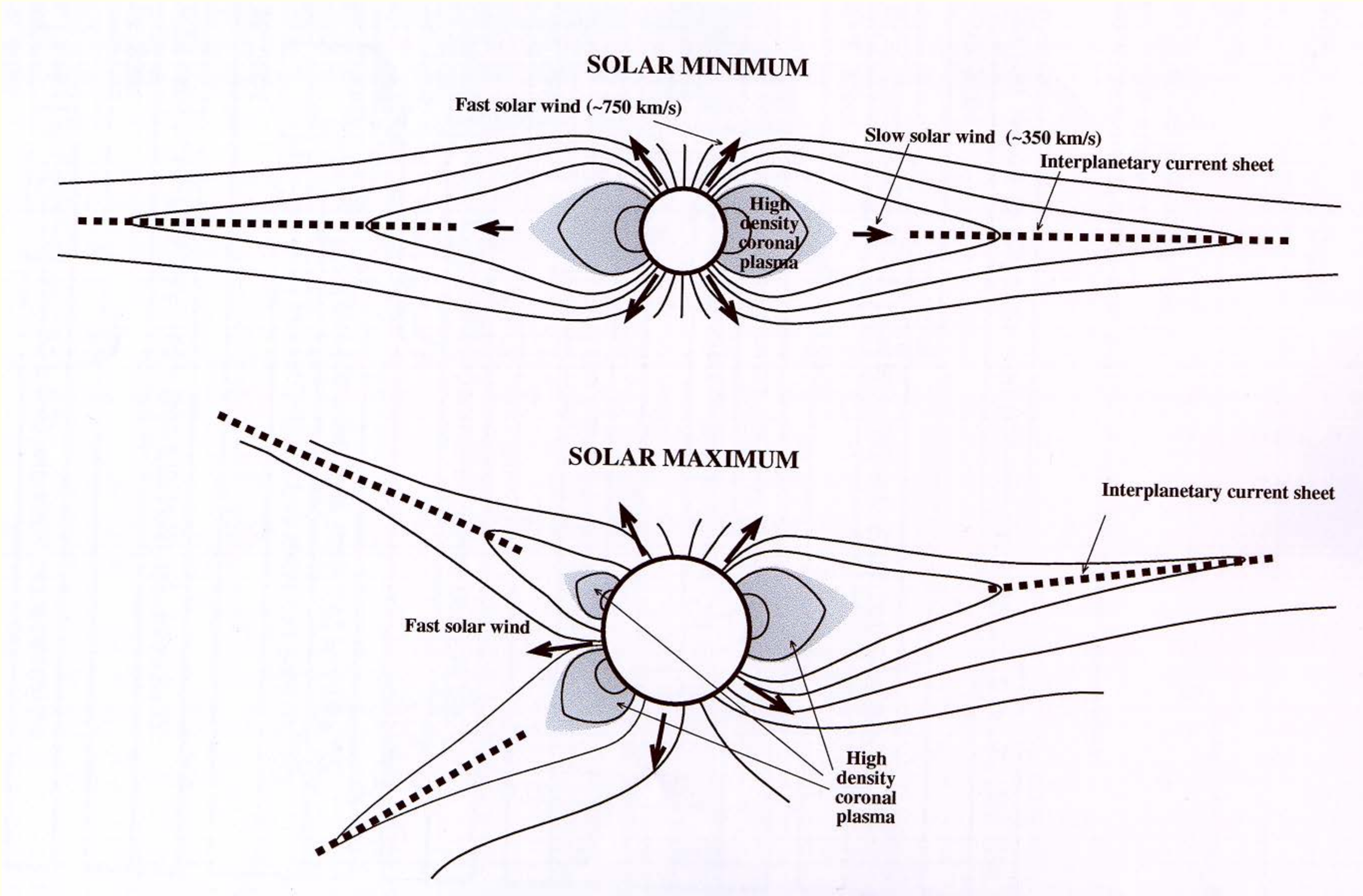
Solar and Heliospheric Observatory (SOHO)
LASCO C2 Coronagraph Movie

Solar wind

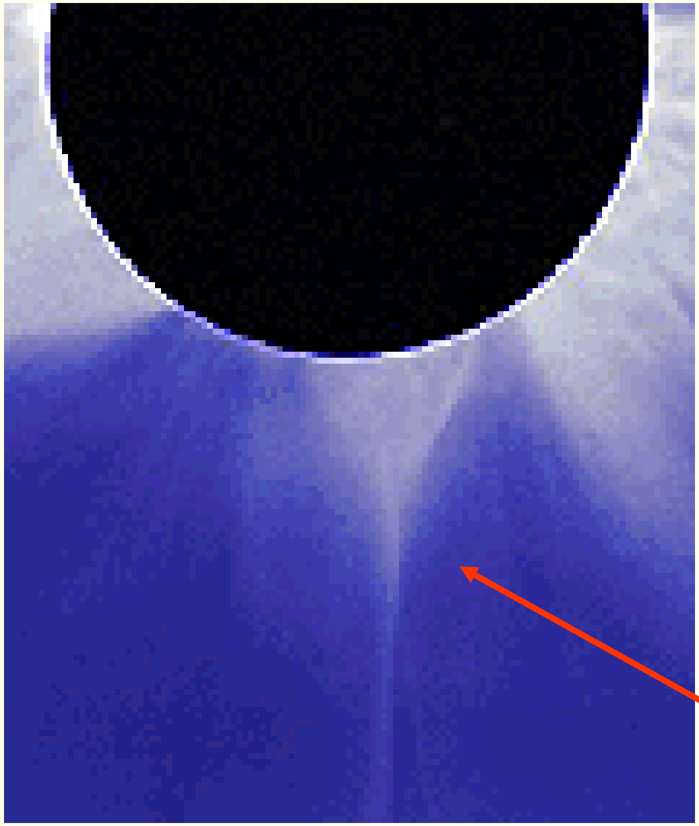
- **Fast solar wind in regions closer to poles**
- **Slow solar wind closer to equatorial plane**

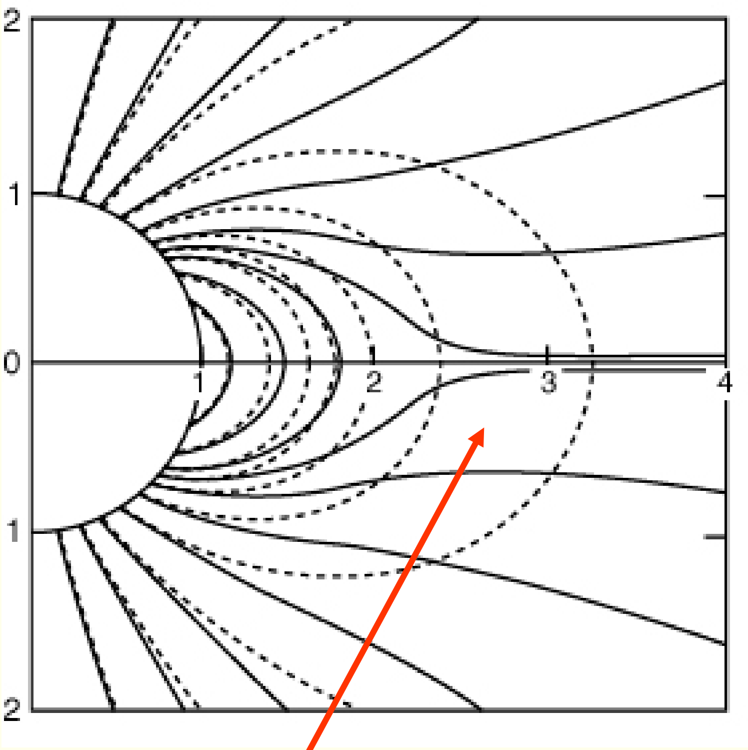


Solar wind


SOLAR MINIMUM
Fast solar wind (~750 km/s)
Slow solar wind (~350 km/s)
Interplanetary current sheet
High density coronal plasma
SOLAR MAXIMUM
Interplanetary current sheet
Fast solar wind
High density coronal plasma

Helmet streamers



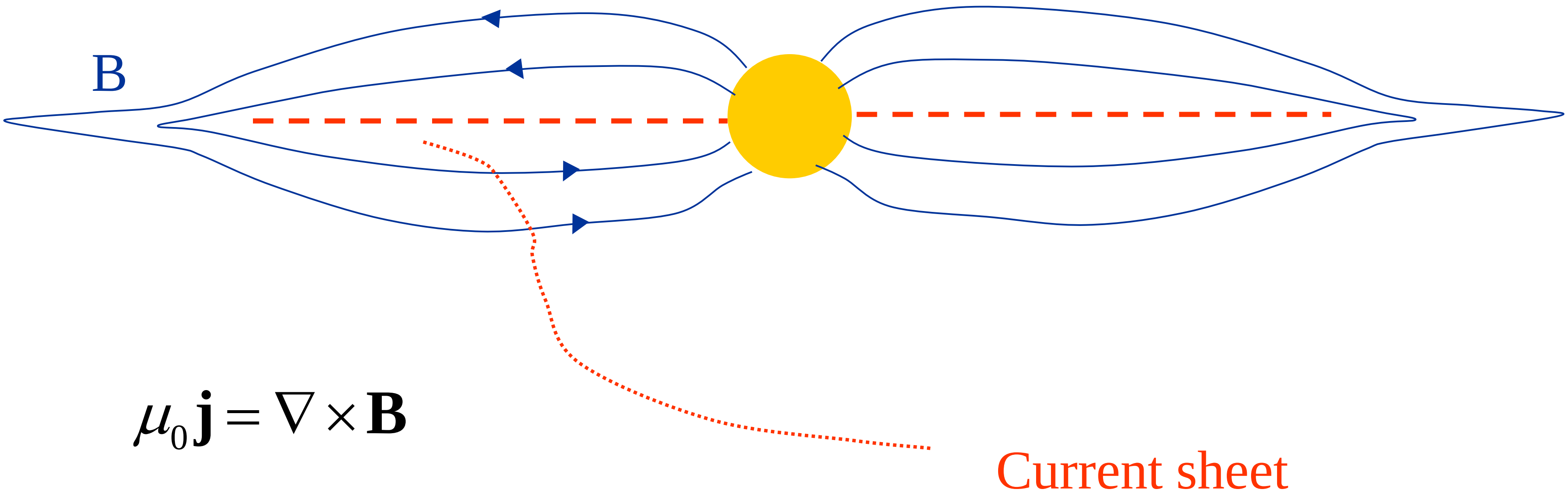


Magnetic field drawn out by solar wind.

This also brakes the solar wind.

Solar wind

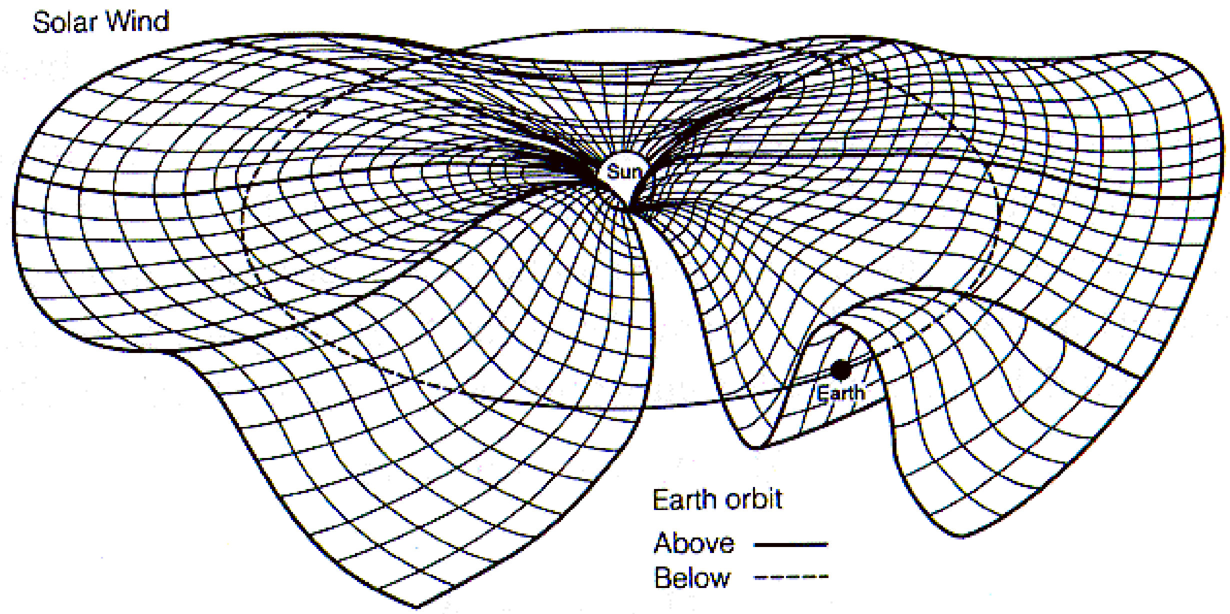
Interplanetary current sheet



$$\mu_0 \mathbf{j} = \nabla \times \mathbf{B}$$

Solar wind

Interplanetary current sheet



Later we will see that the N-S component of the interplanetary magnetic field (IMF is important for the coupling between solar wind and magnetosphere)

Solar wind

Some basic facts

Average values

$n_p = 8\ cm^{-3}$

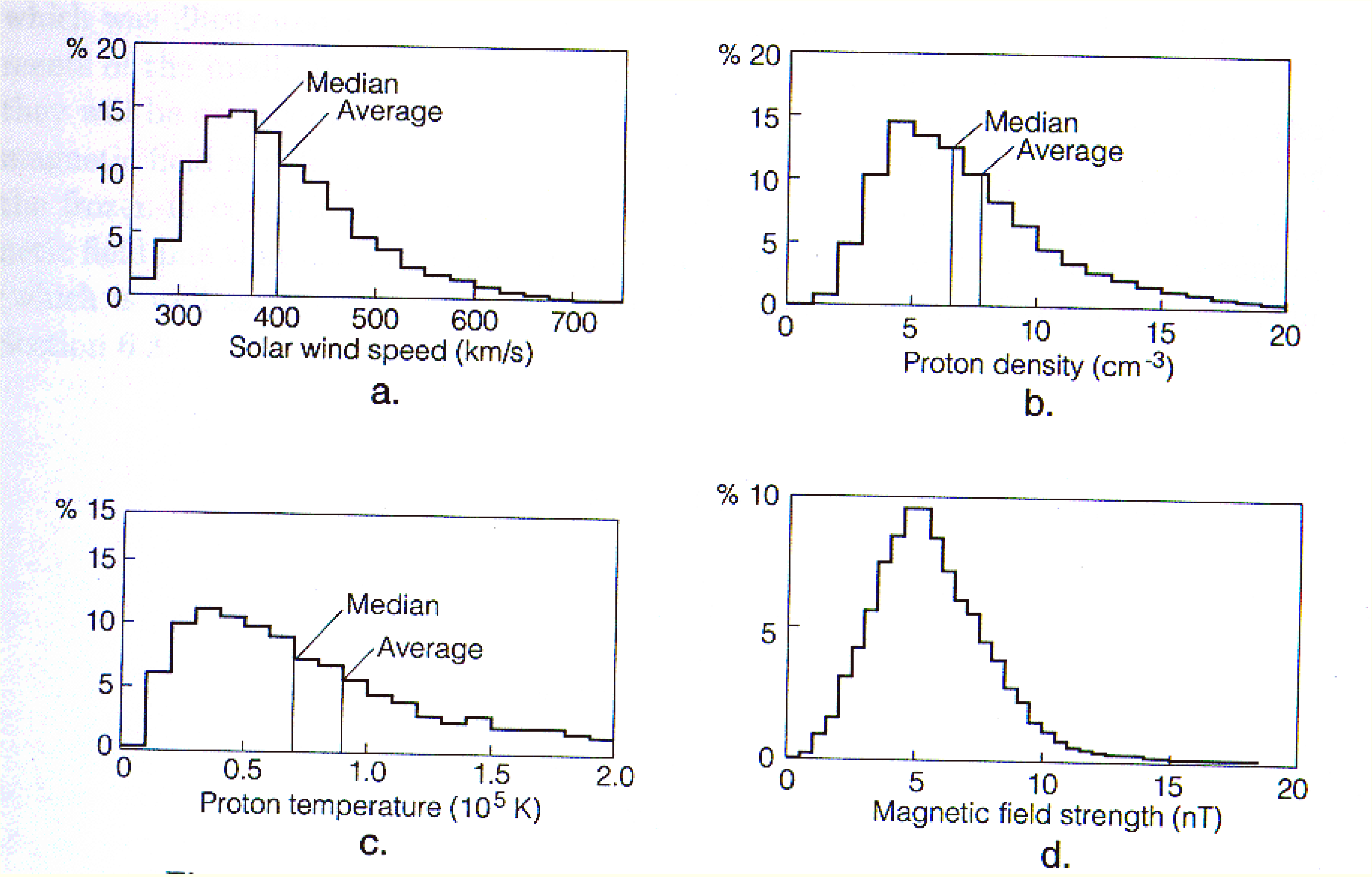
$v = 320\ km/s$

$T_p = 4{\cdot}10^4\ K$

$T_e = 10^5\ K$

$B = 5\ nT$

$\Phi_K = \rho v^3/2 = 0.22\ mW/m^2$



Last Minute!